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WESTERN GEAR CORPORATION

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PRECISION FORGING OF SPIRAL BEVEL GEARS FOR ARMY HELICOPTERS

FINAL REPORT

by:

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SUMMARY

This report presents the results of a fixed level of input, best effort program conducted to develop precision forging techniques for spiral bevel gears with integral teeth forged to pre-grind tolerances by the high-velocity, pneumatic-mechanical forging method. At the successful completion of the primary objective, additional objectives were to demonstrate the strength characteristics and economic advantages to be derived from the process.

A spiral bevel gear and pinion set, which was currently in production for the LOH helicopter main power transmission, was selected for the development effort. Forging dies were designed and manufactured in accordance with proven state-of-art high velocity design criteria and manufacturing practices. Electrode geometry included dimensional allowances for forging heat shrinkage and EDM finishing of the die cavity.

Developmental forging runs were made to establish suitable combinations of forging conditions, including temperature, firing pressure, stroke height and billet size for the gear and pinion forging. In conjunction with the procedure development, inspection of the developmental forgings and dies were conducted.

Initial results from the development phase demonstrated that the spiral bevel gear geometry could be produced by the high velocity closed die forging method, but the dies were subject to premature failure due to upsetting of the die material causing deformation of the spiral bevel tooth form. Die redesign and further development of the forging parameters proved to have a beneficial effect on reducing the conditions contributing to the die tooth deformation, however, subsequent preproduction forging indicated progressive upsetting and bending of the spiral bevel pinion tooth due to high forging forces and the dimensional integrity of the die cavity could not be maintained.

Metallurgical examination of sectioned forgings and tooth segments indicated that preferential grain flow was imparted to the hub in a generally radial direction into the tooth segments, with primary flow extending from toe to heel and dense secondary flow around the tooth root.

Dimensional inspection of the development forgings indicated that the "as-forged" tooth thickness tolerance was within ± .005". Thickness of stock removed per tooth face by profile grinding to obtain the required spiral bevel geometry ranged from .001" to .037" from toe to heel. This condition far exceeded the objective of uniformly removing a maximum of .005" per tooth face. Corrective action to the die was to be obtained by a nominal adjustment

to the EDM in-feed lead for re-finishing the die cavity geometry, however, the gross forging deformation problem that was occurring, principally to a localized area of the die cavity, dictated the need for a die development program before accomplishing the minor adjustment to the spiral bevel geometry.

The mandatory solution of the die deformation problem precluded the meaningful completion of the balance of the program for the development of production forging procedures, dies and forgings for limited fatigue test evaluation.

FOREWORD

This technical report covers the work performed by Western Gear Corporation's Research Department under U.S. Army Contract DAA J01-68-1446 (3G) from January 1968 to April 1970.

The program was accomplished under the direction of Mr. D. Roger Smoak, Project Engineer, U.S. Army Production Equipment Agency, Manufacturing Technology Division, Rock Island, Ill.; and Mr. Robert Vollmer, U.S. Army Aviation Systems Command, St. Louis, Missouri.

The program was performed by Western Gear's Research Department under the general supervision of Mr. M. L. Headman, Director of Research and under the direct supervision of Mr. W. T. Winter, Supervisor of Applied Mechanics. Mr. M. R. Berger was the Project Engineer. Assisting in the project were Research Engineers Mr. C. V. Iverson and Mr. H. Hui.

Sub-contract forging, die design and manufacture were performed by Precision Forge Company, Santa Monica, California under the supervision of Mr. J. Rork, Mr. M. Perry and Mr. V. Marlow. Other sub-contract support for die preparation was provided by Sparkadyne, Inglewood, California, Atlas Tool & Die Company, Los Angeles, California, and Electri-Cal Machining Company, Los Angeles, California. Gear machining was performed by Western Gear's Precision Products Division, Lynwood, California.

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Objectives

Requirements for improved performance and increased production capability of helicopter main power transmissions equipped with spiral bevel gears are continually being made by the military services. Current practices for producing aircraft quality sprial bevel gears require specialized gear cutting and grinding from up-set forgings. Increasing quantities of spur and helical gears are currently being produced by precision forging the gear with integral teeth, imparting a preferential grain flow in and around the tooth and root area and thereby providing a basis for improved fatigue life and performance. Additionally, the process facilitates production by eliminating the gear cutting operation. In order to realize these advantages in spiral bevel gears, a program was initiated for the development of an alternate method for producing spiral bevel gears for army helicopter transmissions. The sub-objectives of the program were to:

a. Determine that a spiral bevel gear configuration can be produced by the high-velocity, pneumatic-mechanical closed die forging method with preferential forging flow being imparted to the tooth elements.

b. Develop die design, fabrication methods and forging procedures for forging spiral bevel gears to pregrind tooth thickness within ± 0.005" and tooth-to-tooth spacing errors within ± 0.0015".

c. Conduct an economic evaluation and feasibility study of the forging process and dies by performing a production forging run consisting of approximately 500 gear sets.

d. Conduct fatigue tests to determine the relative resistance to fatigue failure between forged gears and conventional manufactured gears.

Program Plan

The program was separated into the following four phases:

PHASE I - Development Forging

This phase was to demonstrate that a spiral bevel gear can be forged and removed from a set of closed dies; to establish optimum forging conditions and to define die design parameters for producing uniformly consistent forgings of acceptable tooth thickness and spacing tolerance.

PHASE II - Preproduction Forging

The Preproduction Phase was to evaluate the development die design and procedures on a small lot production basis (approximately 50 pieces) specifically for:

a. Determination of trends in reproducibility and die life;

b. Evaluation of tooling compatibility for production runs;

c. Establishing production run procedures;

d. Providing forged gears for limited fatigue testing.

PHASE III - Production Forging

To demonstrate production capability, reproducibility and economic evaluation from forging 500 gear sets.

PHASE IV - Limited Fatigue Testing

To determine the relative resistance to fatigue failure of forged gears versus conventional manufactured gears.

Program Facilities

The principal equipment facilities that were utilized on the program are shown in Figures 1 through 5. All forged development was performed with the illustrated high-velocity, pneumatic-mechanical forging machine which operates on high pressure gas to drive the ram at speeds up to 1200 in./sec. The machine is designed to feedback the reaction force into its own structure so that little force is imparted to the foundation. With proper die and billet design and close regulation of gas firing pressure, ram height and billet temperature, most of the energy is absorbed in the deformation of the forged part. Close control of these variables makes the process highly repeatable, thus permitting close tolerance forging. In conventional production of spiral bevel gearing, the tooth profiles are cut on a Gleason Hypoid Generator and finished to size on a Gleason Hypoid Grinder. For the purposes of this program, the generator was used to cut the electrode teeth for die manufacture. Finishing and stock removal evaluations of the precision forged gearing was accomplished in the Gleason Hypoid Grinder. The Gleason Bevel Gear Blank Checker and Universal Tester were used for inspection evaluation purposes.

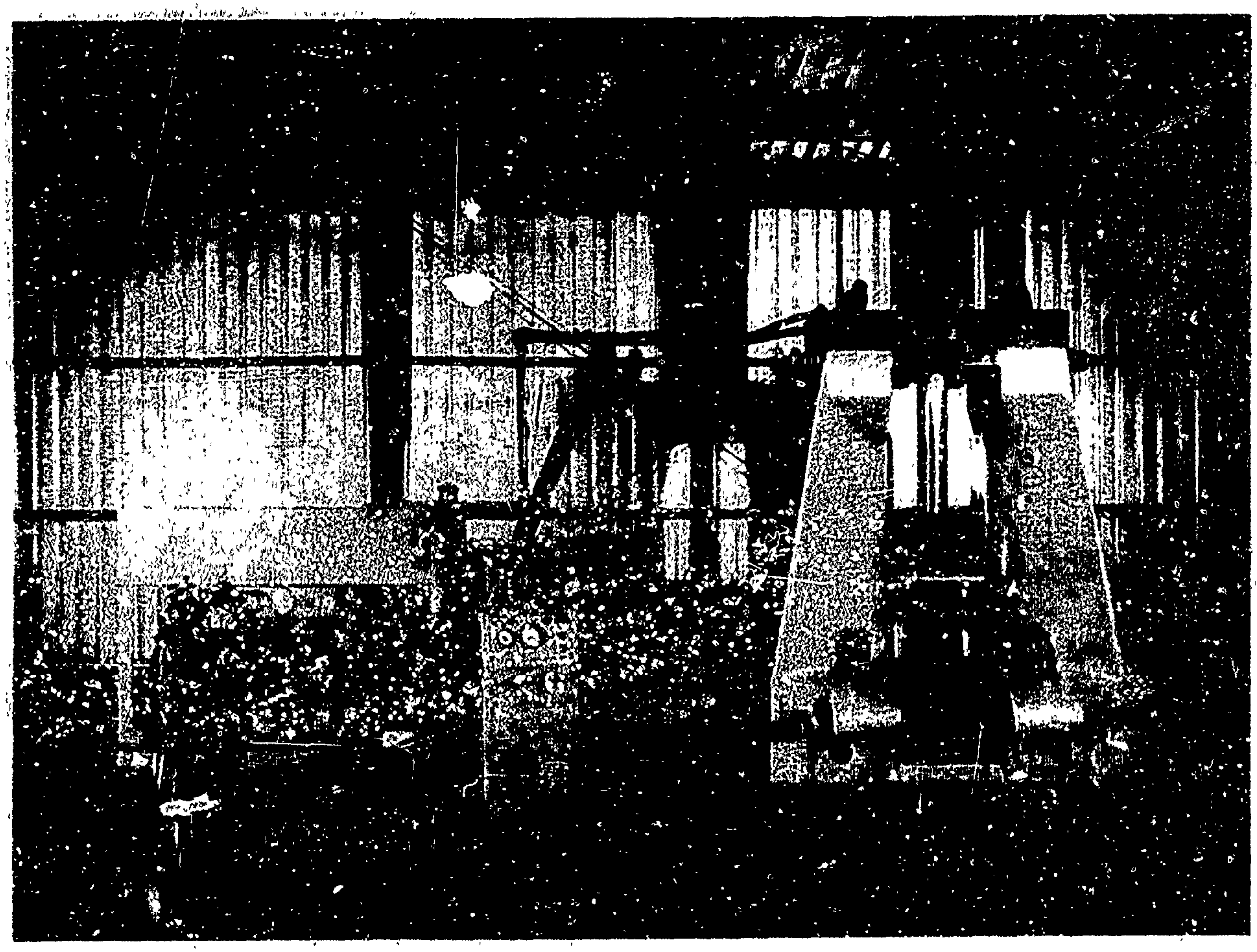

Figure 1. High Velocity Forging Machine

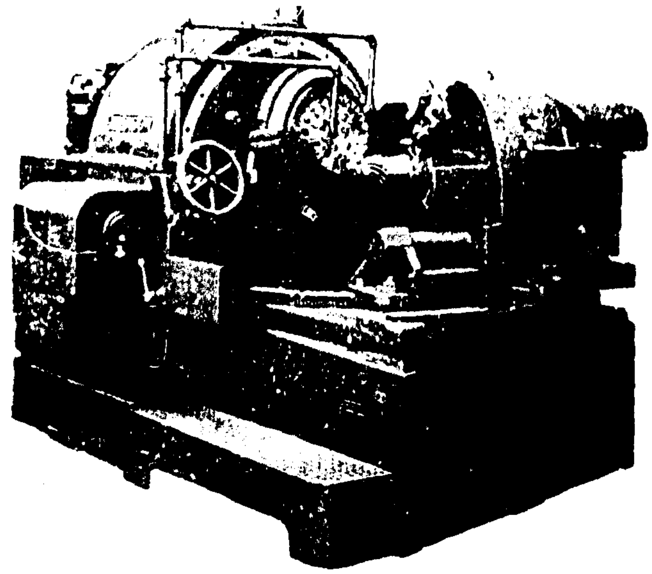

Figure 2. Gleason No. 26 Hypoid Generator

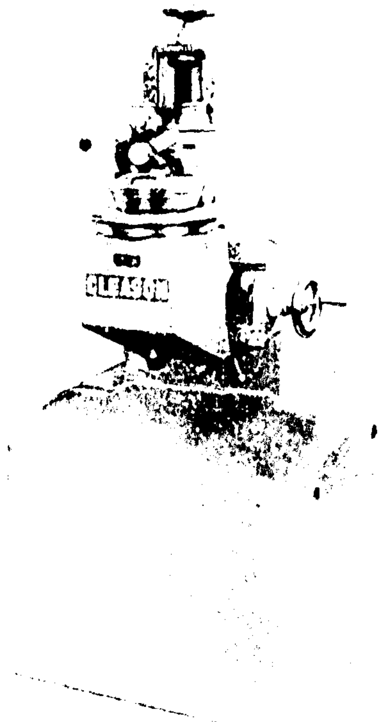

Figure 3. Gleason No. 15
Bevel Gear Blank Checker

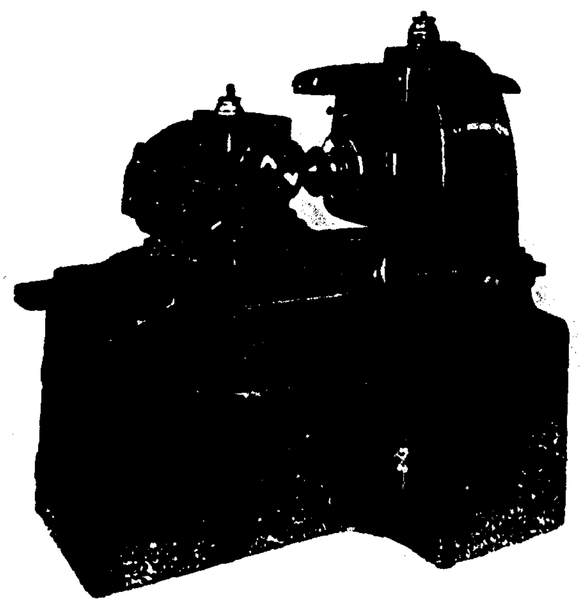

Figure 4. Gleason No. 13
Universal Tester

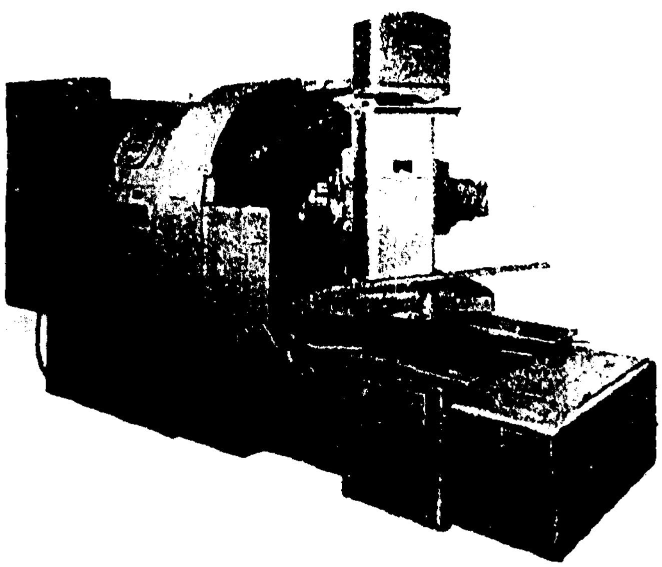

Figure 5. Gleason No. 27
Hypoid Grinder

PHASE I - DEVELOPMENT FORGING

Forging Dies

The spiral bevel gear set that was selected for this program was the high speed reduction set used in the main power transmission unit for the OH-6A Army "Cayuse" helicopter (Figure 6). The transmission was designed and produced by Western Gear Corporation. The gear set consisted of a shank type, 15 tooth spiral bevel gear pinion and a 44 tooth mating gear as shown and described in Appendix I.

The 44 tooth spiral bevel gear was selected for initial development of the die and forging procedures in preference to the pinion for the following reasons:

a. It offered a better degree of forgeability due to a larger mass with less heat loss effects.

b. It presented less difficulty in sinking the spiral bevel tooth form into the die cavity due to a larger cone angle than that of the pinion.

c. It provided larger over-all dimensions for verification of calculated heat shrink factor.

Die Design

The basic forging concept used for both the gear and pinion was to develop the finished part in three forging steps. Starting with bar stock billets, a preform (up-set) was forged in closed dies to produce an approximate shape of the gear body. This was followed by a blocking operation to develop the tooth segments nearly to finish size. The third step forged the gear to final size. The forging sequence, configurations and corresponding die arrangements that were designed and used for the development of the pinion and gear forgings are illustrated in Figures 7 and 8. The method for removing the pinion forging from the die was to unwind the part from the spiral bevel cavity by applying a twisting force to the shank (long shank end of forging). In order to apply this same method to the gear, it was necessary to include a stub shaft (2-1/2" diameter x 1-1/2" long) to the heel end of the forging.

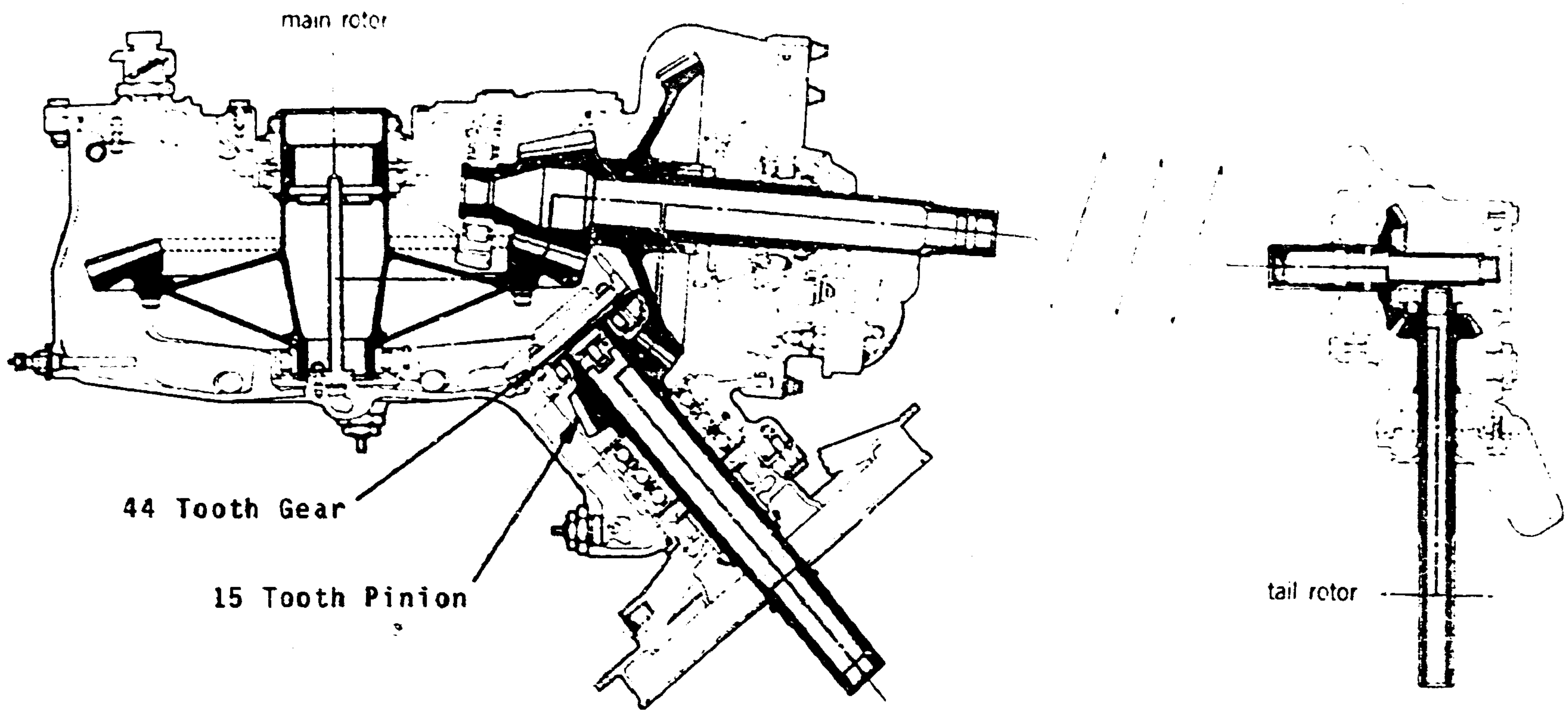

Figure 6. OH-6A Army "Cayuse" Helicopter Main Power Transmission Unit

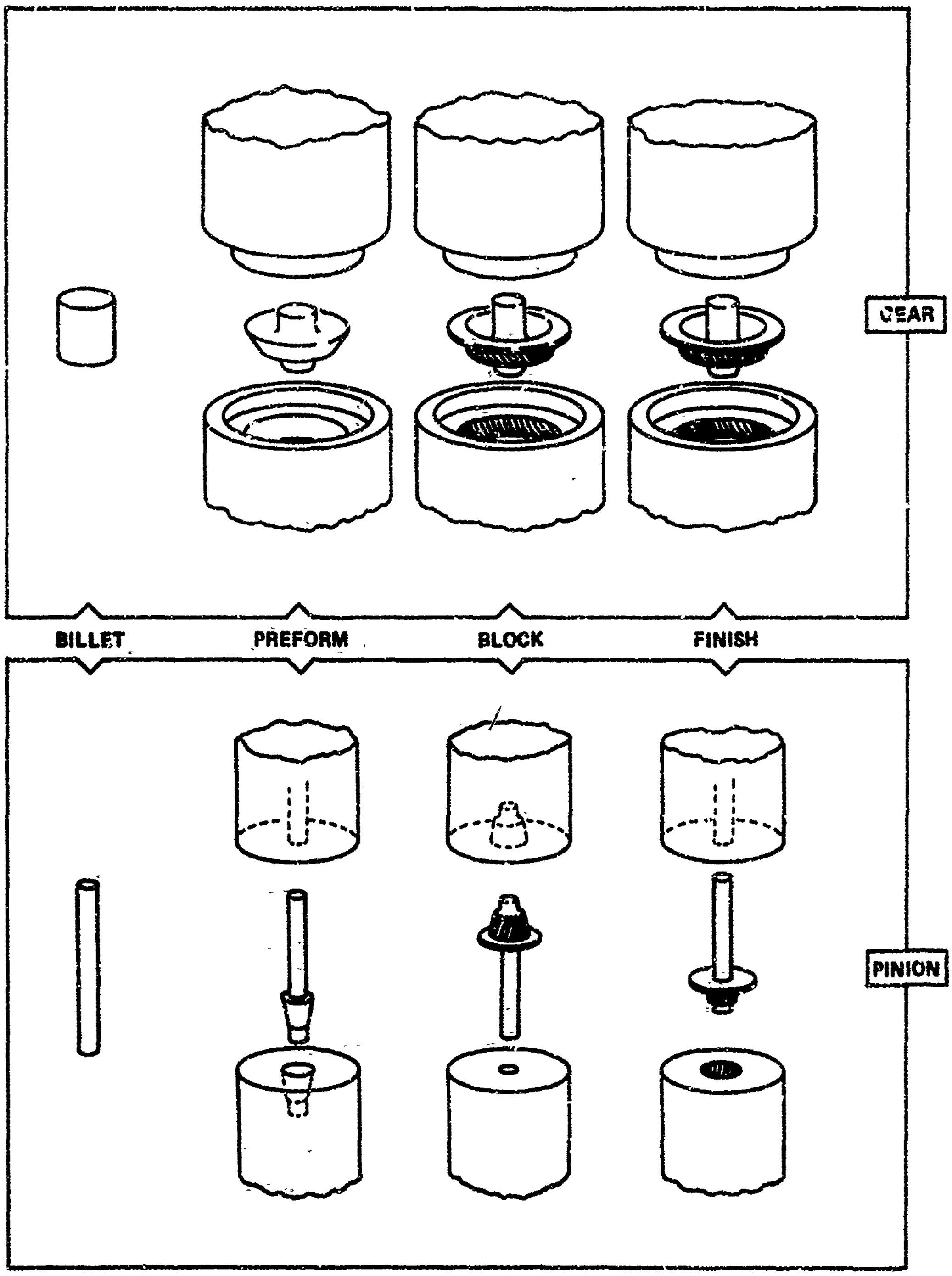

Figure 7. Forging Steps and Die Arrangements Used for Pinion and Gear Forgings

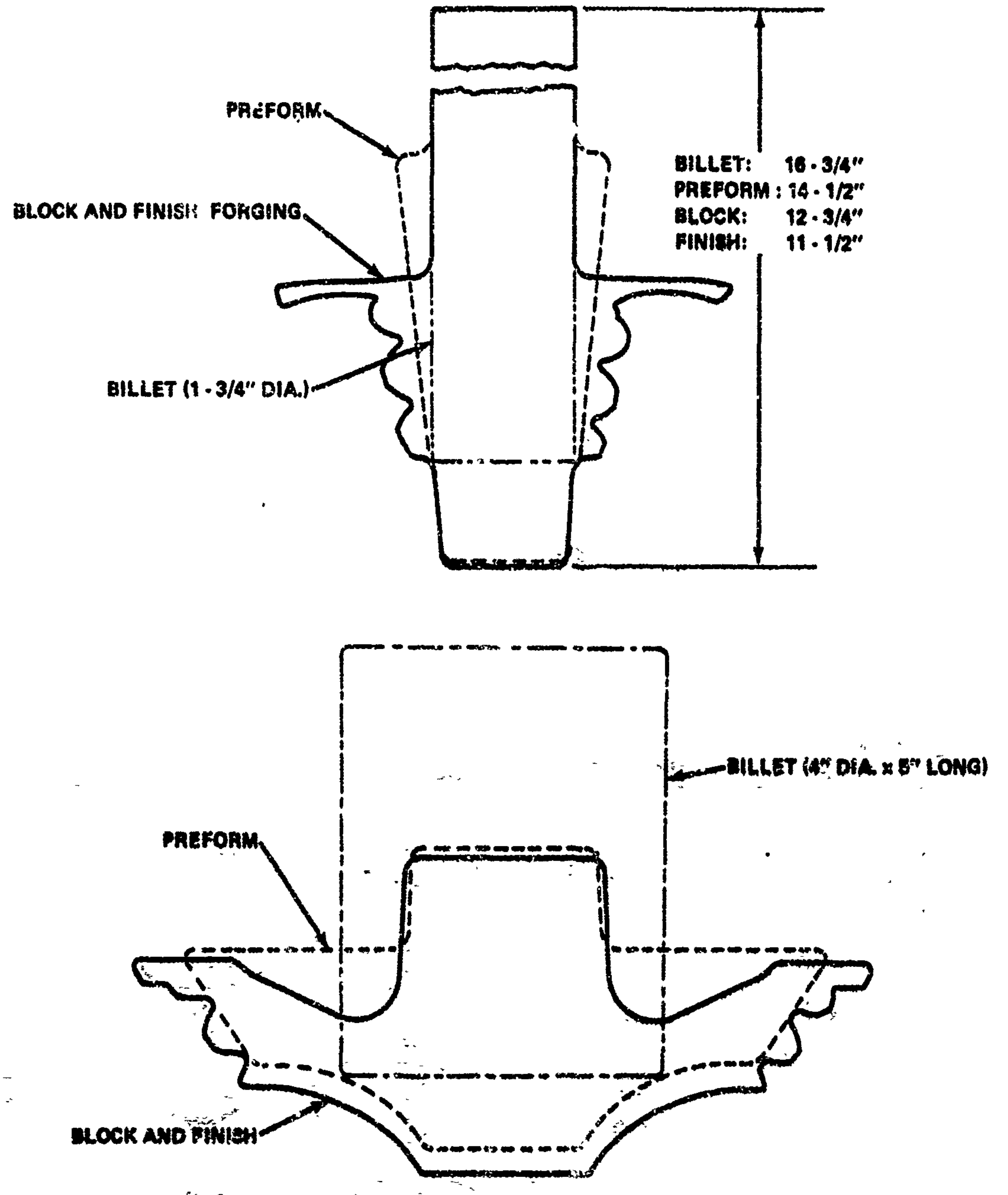

Figure 8. Cross-sectional Representations of the Spiral Bevel Gear and Pinion from Billet to Finish Forging

Die Material

Die materials selected and used for the fabrication of the various die sets are shown in Table I. Selection was predicated on results and experience obtained by Precision Forge Company and Western Gear Corporation from prior high velocity forging development and production work with spur gears and similar configurations. The objective of the selection was to obtain sufficient strength and wear properties without sacrificing toughness. In consideration of the protruding spiral bevel tooth segments that would obliquely obstruct metal flow and be subjected to high impact forces, the selection favored higher toughness, rather than strength and wear resistance.

Die Manufacture

Die sets were manufactured by machining finish heat treated die blocks to the required internal and external finish dimensions, except for the spiral bevel tooth portion of the die cavity. The finish tooth geometry was produced in the die cavity by electrical discharge machining (EDM) with brass electrodes shown in Figure 9. The electrode spiral bevel teeth were cut on a Gleason Hypoid Generator, in the same manner as regular production gears and pinions except that a slightly modified cutting schedule was used. The modification provided for a dimensional allowance to the generated tooth geometry for the forging heat shrink effects (0.0125"/") and EDM spark gap clearance (0.002" per surface). From an analysis that was conducted to determine the shrink characteristics of forged spiral bevel gears (Appendix II) it was determined that:

a. The displacement of any point in an elastic body subjected to temperature change is proportional to its position, i.e., linear expansion is proportional to its linear dimension.

b. Spiral angle does not change due to expansion.

c. In reference to the gear axis, the radial expansion of the surface of the gear tooth is proportional to its distance from the axis.

The electrode designs are given in Appendix III.

The EDM in-feed guide system for providing and controlling the correct amount of rotational movement to the electrode in conjunction with the linear in-feed was accomplished by means of a helix slotted sleeve and pin arrangement, as shown in Figure 10. The slot helix was based on an averaged cylindrical lead of the respective pinion or gear tooth profile surfaces. The EDM procedure

Table I
Die Materials

Die Sets	Gear	Pinion
Preform - Punch	Durodi, Temper I 12"øx12"; R_c42-46	Durodi, Temper I 12"øx12"; R_c42-46
Preform - Die	Durodi, Temper I 12"øx12"; Rc42-46	Durodi, Temper I 12"øx12"; Rc42-46
Block - Punch	Durodi, Temper I 12"øx12"; Rc42-46	Durodi, Temper I 12"øx12"; Rc42-46
Block - Die	Durodi, Temper I 20"øx18"; Rc42-46	Durodi, Temper I 12"øx12"; Rc42-46
Finish - Punch	Durodi, Temper I 12"øx12"; Rc42-46	Durodi, Temper I 12"øx12"; Rc42-46
Finish - Die	AISI Type H-11 20"øx18"; Rc42-46 2nd die: Durodi, Temper I	Durodi, Temper I 12"øx12"; Rc42-46

	AISI Type H-11		Durodi	
	Nominal	Check Analysis	Nominal	Check Analysis
C	.35	.37	.55	.54
Mn		.21	.60	.56
S		.026		.023
Si		.99	.85	.73
Ni			1.55	1.66
Cr	5.00	5.03	1.00	.90
V	.40	.37		
Mo	1.50	1.26	.80	.69
Cu		.11		.15
P		.024		.004
Hardness Rc		42-44		42-44

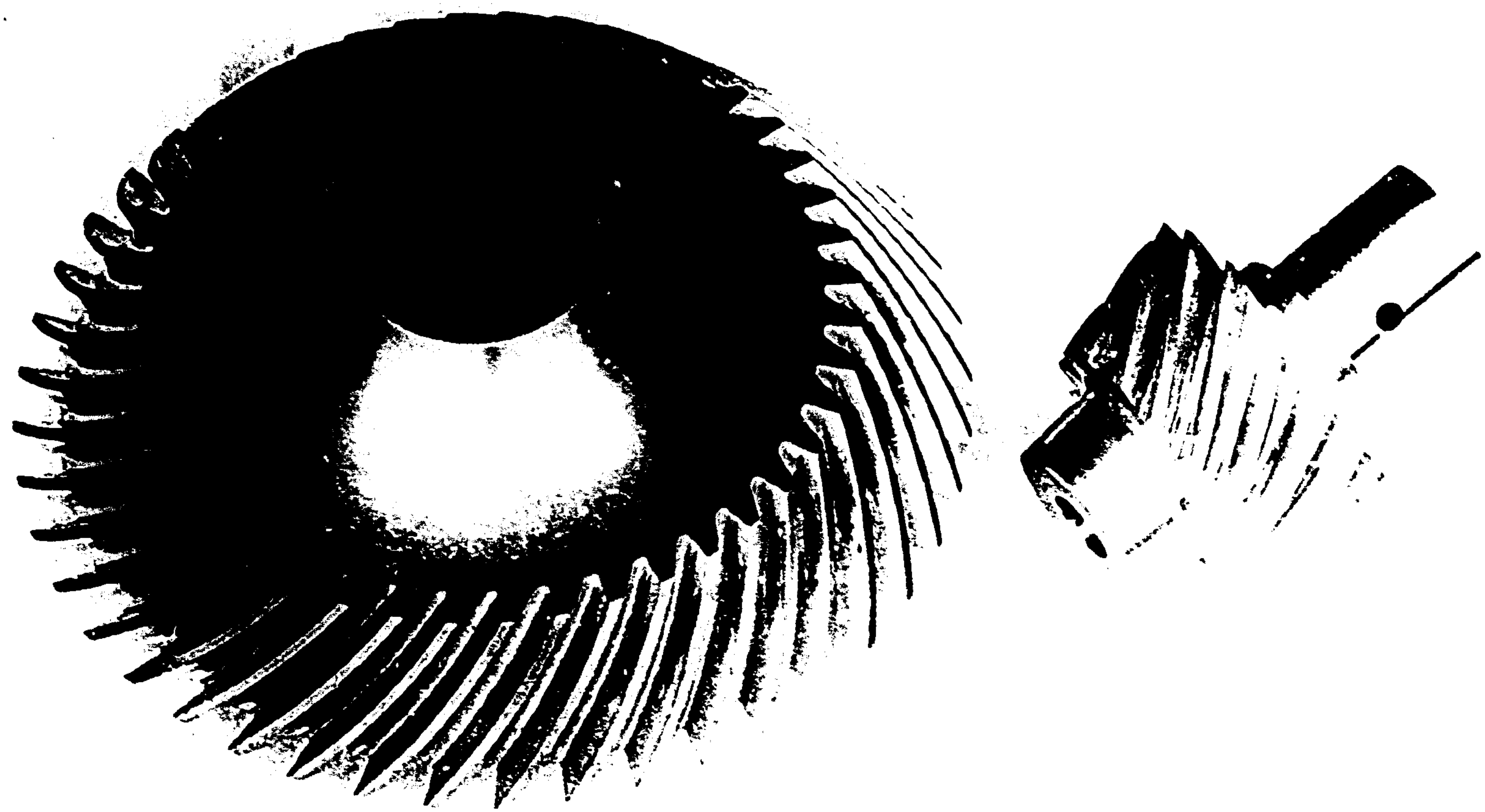

Figure 9. Pinion and Gear EDM Brass Electrodes

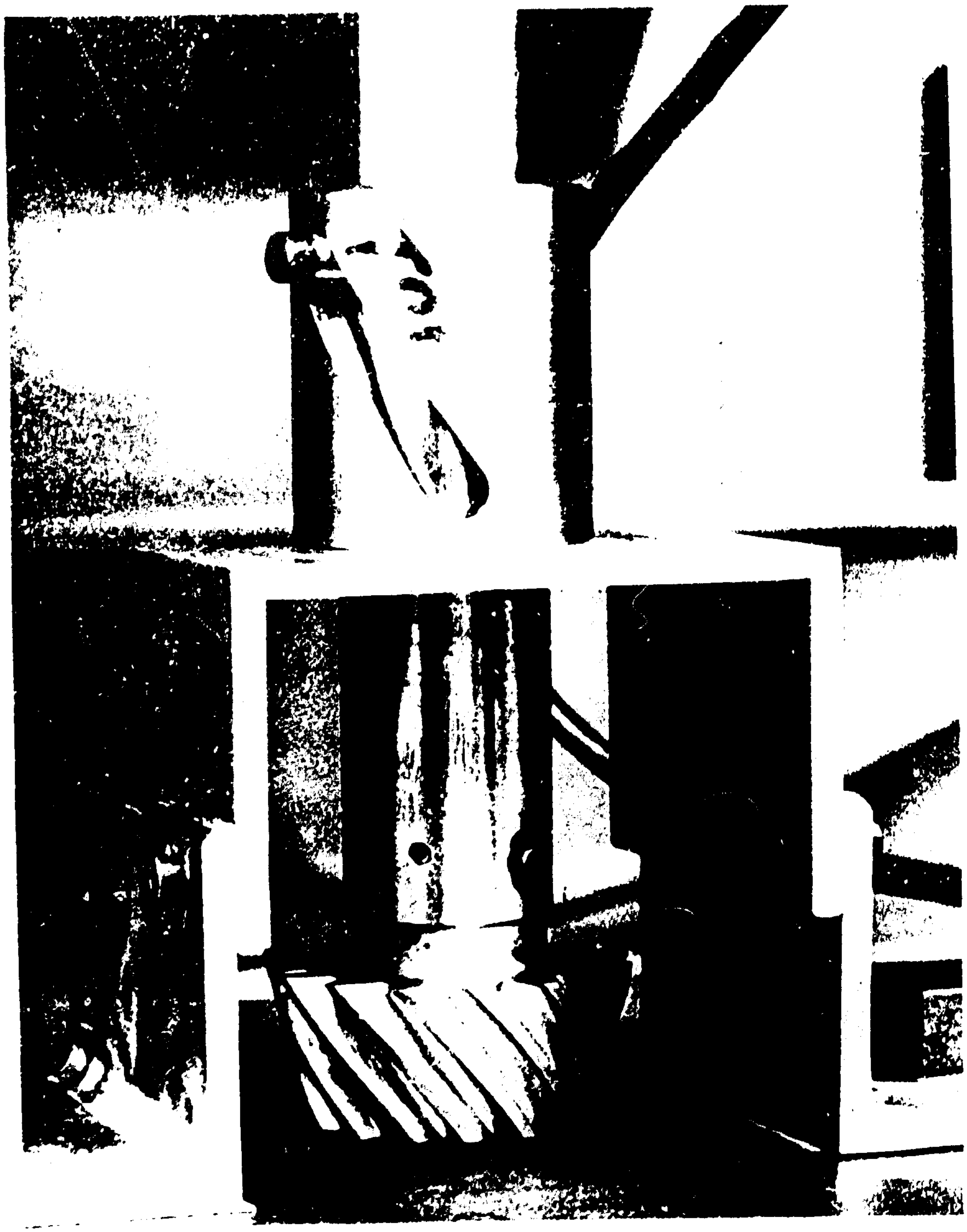

Figure 10. EDM Finishing of Pinion Die Cavity

used to finish the block and finish die cavities was to complete the finish die first with six new electrodes and then process the block die with the worn electrodes which provided a desired under-size tooth form for the blocking operation. When changing from a used electrode to a new electrode, provision was made to properly time the new electrode into the cavity.

Dimensional checks were performed before the dies (Figures 11 and 12) were removed from the EDM set-up, and Cerro alloy casts with shaft inserts positioned by the EDM electrode holder were made. These casts provided a means for inspection of the die tooth geometry on the Gleason Bevel Gear Blank Checker, which otherwise could not be inspected prior to producing a forging. The die casts also served as a forging die reference for determining die degradation.

Forging Material

The forging stock used for the program was AMS 6265 (consumable electrode vacuum remelt AISI 9310), a commonly used aircraft quality carburizing grade gear material. In addition, a small quantity of AISI 1018 was used during the forging development phase as a supplementary material to facilitate the macro evaluation of the forging flow characteristics. A total quantity of 21,500 pounds of 1-3/4" and 4" diameter mill length bars were obtained of which 15,150 pounds were from a single heat of steel in both bar sizes. Gears for limited fatigue testing (precision forged sets and conventional manufactured sets) were to be obtained from this single heat lot of material.

The forging material specification requirements, certification and check analysis results are shown in Table II.

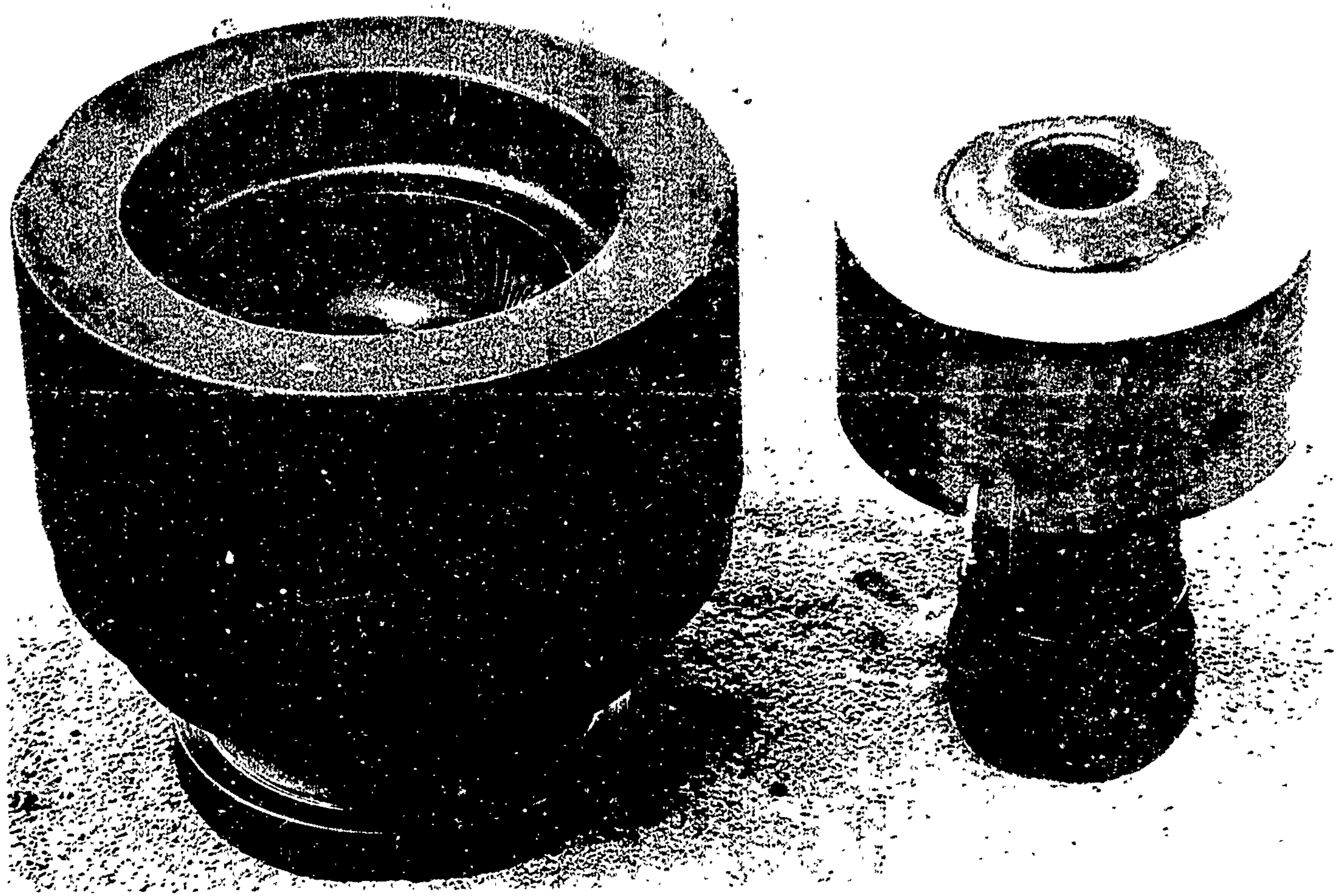

Figure 11. Die Set for High Velocity Forging Spiral Bevel Gears

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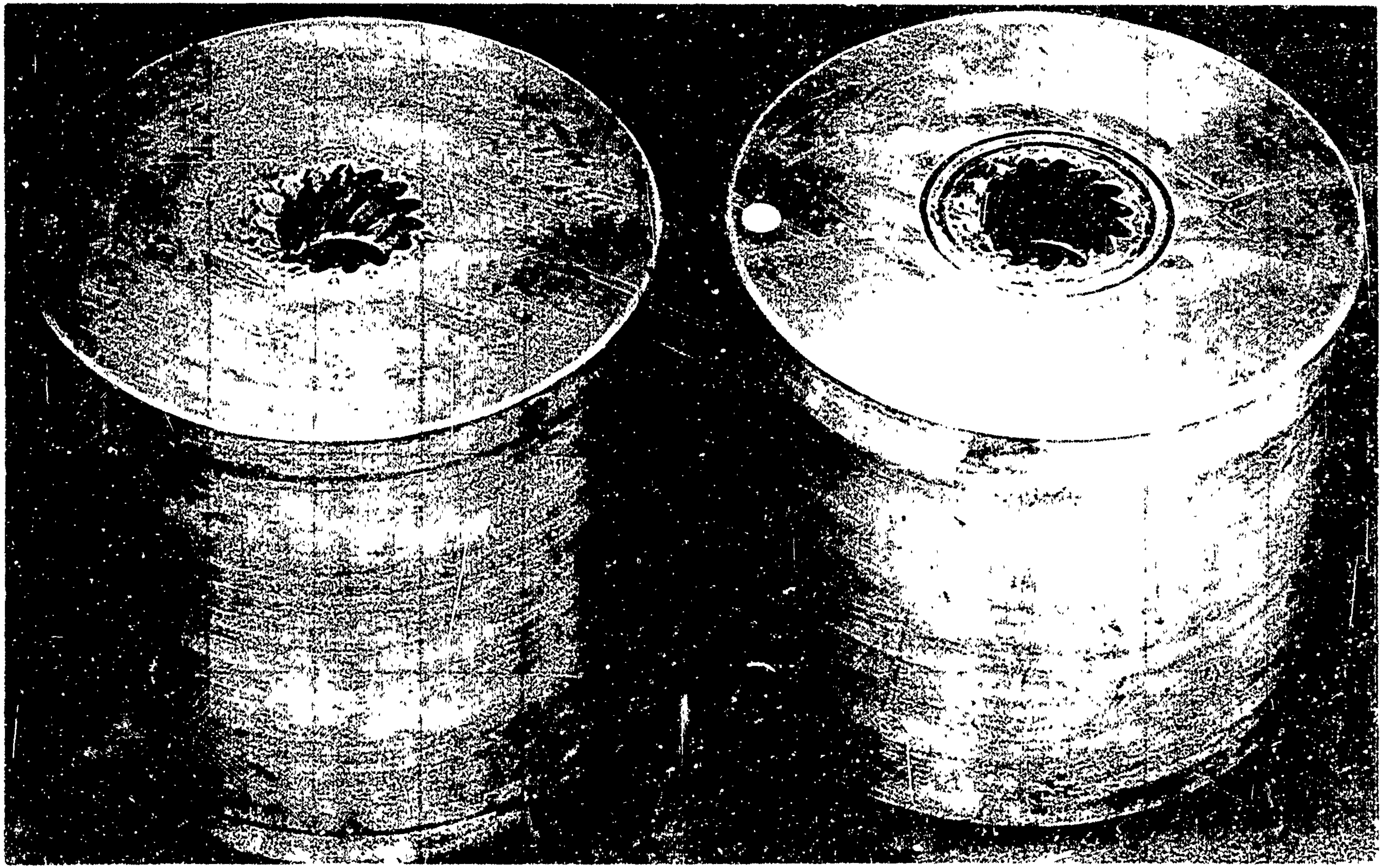


Figure 12. Spiral Bevel Pinion Block and Finish Dies

Table II
Specified and Test Properties of Forging Materials

Properties	AMS 6265	Mill Cert. Ht. #52916	Check Anal. Ht. #52916
Chemical:			
C	.07-.03	.11	.10
Mn	.40-.70	.61	.63
P	.025 max	.007	.011
S	.025 max	.005	.010
Si	.20-.35	.31	.23
Cr	1.00-1.40	1.33	1.35
Ni	3.00-3.50	3.27	3.27
Mo	.08-.15	.15	.16
Grain Size:	5 or finer; few to 3	Avg. 7	5-7
ASTM E45 Micro-Cleanliness:			
A-thin	**2.0 max**	<1.0	0
A-heavy	**1.0 max**	0	0
B-thin	**1.5 max**	0	0
B-heavy	**1.0 max**	0	0
C-thin	**1.5 max**	0	<1.0
C-heavy	**1.0 max**	0	0
D-thin	**1.5 max**	0.5-1.0	0
D-heavy	**1.0 max**	0	0

FORGING PROCEDURE DEVELOPMENT

Spiral Bevel Gear Forging

Initially, a five piece trial lot of gear billets were used to obtain "a feel" for the forging characteristics and response to the preforming, blocking and finishing operations. This was conducted in a very conservative type of trial-and-error approach regarding the forging parameters used, i.e., high forging temperature, low firing pressure, short punch strokes and multiple hits, so as to avoid possible forge conditions that might result in accidental die breakage. The first lot of high velocity forge produced spiral bevel gears with integral forged teeth, resulting from this effort, is shown in Figure 13. The information obtained, provided a basis for initiating the development and refinement phase of the gear forging procedures. The forging parameters, conditions and notations of this effort are tabulated in Table III.

The following supplemental procedures were utilized in conjunction with the forge development program:

a. All billets were prepared from hot rolled bars by abrasive saw cut to the required length, deburred and abrasive cleaned (Wheelabrator).

b. Forging parts were heated in a temperature controlled, gas fired, conventional type furnace, with the combustion adjusted to provide a gas rich, reducing atmosphere.

c. Intermediate forged parts were abrasive cleaned and magnaflux inspected.

d. Forged parts were free-air cooled after removal from dies.

e. Die sets were pre-heated to 200°/300°F.

f. Forged parts were serialized by lot and piece number.

Preform forge conditions for reducing the 4" diameter x 5" long gear billets to the preform shape were readily established at the following conditions: 2050°F forge temperature; two hits: First at 1900 psi firing pressure and 23" stroke and second hit at 950 psi firing pressure and 12" stroke. Satisfactory block forging conditions were derived without extensive development at the following conditions: 2100°F forging temperature, one hit at 1580 psi and 22" stroke.

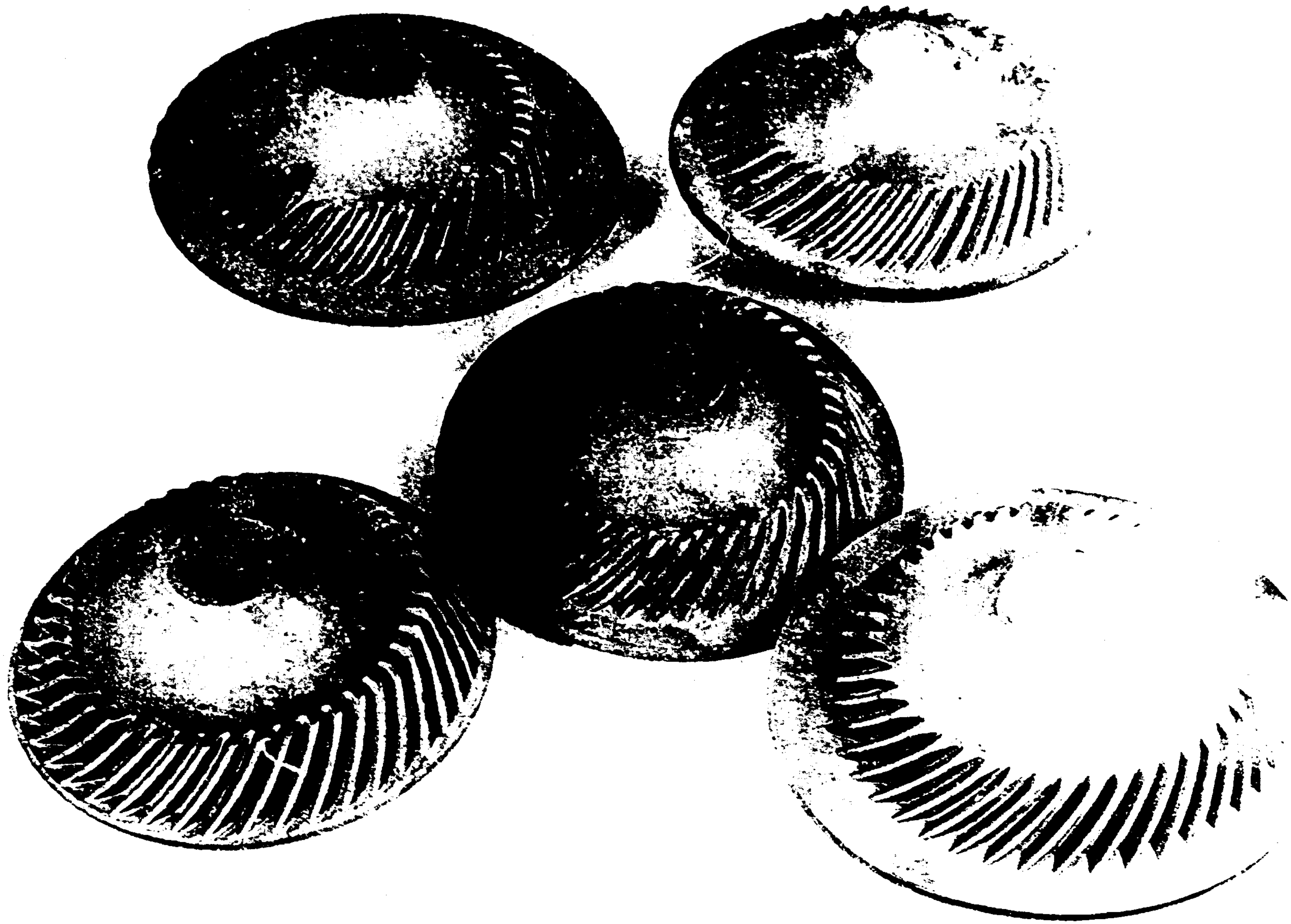


Figure 13. First Lot of High Velocity Forged Spiral Bevel Gears

Table III
Development Forging Parameters for Spiral Bevel Gear (44 Teeth)

Forging Conditions

Forging Operation	Forging No. Lot-Pc.	No. of Hits	Furn. Temp. °F.	Stroke Height in.	Firing Pressure psi	Notations
Preform (6 pcs)	2-1	1	2050	23	1900	Billet data: 4" round by 5" long, 18.3 lbs., AMS 6265.
		2		6	700	
		3	2050	12	950	Preforms Nos. 2-1 & 2-2 were not completely
"	2-2	1	2050	23	1900	formed after 2nd hit. Pressure & stroke of 2nd hit
		2		6	700	was increased for 2-3, 2-4 & 2-5. First 2 pieces
		3	2050	12	950	were reheated & given 3rd hit to complete filling.
"	2-3	1	2050	23	1900	
		2		12	950	
"	2-4	1	2050	23	1900	7 to 10 seconds elapsed between 1st and 2nd hit: 25
		2		12	950	to 30 seconds interval per operation.
"	2-5	1	2050	23	1900	
		2		12	950	
"	2-6	1	2050	23	1900	
		2		12	950	
Block (6 pcs)	2-1	1	2050	28	1600	The preform forgings were completely abrasive cleaned (Wheelabrator) prior to block forging.
"	2-2	1	2050	28	1600	

Table III - continued

Development Forging Parameters for Spiral Bevel Gear (44 Teeth)

Forging Conditions

Forging Operation	Forging No. Lot-Pc.	No. of Hits	Furn. Temp. °F	Height in.	Firing Pressure psi	Notations
Block (6 pcs)	2-3	1	2050	28	1600	Blocked forgings were abrasive cleaned, and magnafluxed; no indications.
"	2-4	1	2050	28	1600	
"	2-5	1	2050	28	1600	
"	2-6	1	2050	28	1600	
Finish (6 pcs)	2-1	1	1775	12	1200	Tooth section not completely filled.
		2		12	1200	Did not completely fill.
		3	re-heated 1775	16	1400	Part bounced; tooth section damaged.
"	2-2	1	1775	12	1200	Appearance good; tooth section filled.
"	2-3	1	1775	16	1400	Convex side at toe did not fill.
		2	re-heated 1775	16	1400	Part bounced; tooth section damaged.
"	2-4	1	1775	12	1200	80% convex face from toe did not fill.

Table III - continued
Development Forging Parameters for Spiral Bevel Gear (44 Teeth)

Forging Conditions

Forging Operation	Forging No. Lot-Pc.	No. of Hits	Furn. Temp. °F	Stroke Height in.	Firing Pressure psi	Notations
Finish (6 pcs)		2	re-heated 1775	12	1200	Did not completely fill.
		3	re-heated 1775	12	1200	Filled fairly well; could not be reht again due to flash being too thin. Die tooth sections at parting face showed evidence of deformation (rolling over & downward). Die was removed and .030" facing cut made & ends of tooth sections chamfered.
"	2-5	1	1775	12	1200	Increased amount of lubricant applied to die cavity. Part bounced & tooth section was chopped.
		2	re-heated 1775	16	1400	Chopped condition was partially eliminated.
		3	re-heated 1775	16	1400	Chopped condition was almost eliminated except for small ding.
"	2-6	1	1775	16	1400	Small amount of lubricant applied & thoroughly air blasted for uniform dispersion. Tooth section appeared to be good.

Table III - continued

Development Forging Parameters for Spiral Bevel Gear (44 Teeth)

Forging Conditions

Forging Operation	Forging No. Lot-Pc.	No. of Hits	Furn. Temp. °F	Stroke Height in.	Firing Pressure psi	Notations
Finish (1 pc)	3-1	1	2000	18	1800	Die broke due to excessive forging conditions & flash thinning.
Preform (37 pcs)	4-1 thru 4-37	1	2050	23	1900	Billet data: 4" round by 5" long, 18.3 lbs., AMS 6265.
		2		12	950	
Block (37 pcs)	4-1 thru 4-31	1	2100	22	1580	
	4-32 thru 4-37	1	2000	15	1500	
		2	re-heated 2000	15	1500	
Finish (31 pcs)	4-31	1	2100	4	1000	Tooth section not completely filled.
"	4-18	1	2100	4	1000	Tooth section not completely filled.
"	4-1	1	2100	6	1000	Tooth section not completely filled.
	4-3	1	2100	5	1000	Tooth section not completely filled.
	4-4	1	2100	5	1000	Part bounced & teeth chopped.

Table III - continued
Development Forging Parameters for Spiral Bevel Gear (44 Teeth)

Forging Conditions

Forging Operation	Forging No. Lot-Pc.	No. of Hits	Furn. Temp. °F	Stroke Height in.	Firing Pressure psi	Notations
Finish (31 pcs)	4-6	1	2100	4	1000	Part bounced & teeth chopped.
"	4-7	1	2100	4	1000	Part bounced & teeth chopped.
"	4-8	1	2100	4	1000	No chop.
"	4-9	1	2000	4	1000	No chop.
"	4-10	1	2000	4	1000	Part bounced & teeth chopped.
"	4-11	1	2000	3	900	Part bounced & teeth chopped.
"	4-12	1	2000	3	900	No chop.
"	4-13	1	2000	6	1000	No chop.
"	4-14	1	2000	6	1000	Part bounced & teeth chopped; locking hook ground in bottom radius of die cavity.
"	4-16	1	1950	6	1600	No bounce; some lack of fill at toe on convex face which was not noticeable when hot.
"	4-17	1	1950	6	1600	No bounce; some lack of fill at toe on convex face which was not noticeable when hot.
"	4-19	1	1950	6	1600	No bounce; some lack of fill at toe on convex face which was not noticeable when hot.

Table III - continued
Development Forging Parameters for Spiral Bevel Gear (44 Teeth)

Forging Conditions

Forging Operation	Forging No. Lot-Pc.	No. of Hits	Furn. Temp. °F	Stroke Height in.	Firing Pressure psi	Notations
Finish (31 pcs)	4-20	1	1950	6	1600	No bounce; some lack of fill at toe on convex face which was not noticeable when hot.
"	4-21	1	1950	6	1600	No bounce; some lack of fill at toe on convex face which was not noticeable when hot.
"	4-22	1	1950	6	1600	No bounce; some lack of fill at toe on convex face which was not noticeable when hot.
"	4-24	1	1950	6	1600	No bounce; some lack of fill at toe on convex face which was not noticeable when hot.
"	4-25	1	1950	6	1600	Part bounced & teeth chopped.
"	4-26	1	1950	6	1600	No bounce or chop.
"	4-27	1	1950	6	1600	No bounce or chop.
"	4-28	1	1950	6	1600	Bounced and chopped.
"	4-29	1	1950	6	1600	No bounce or chop.
"	4-30	1	1940	6	1600	No bounce or chop.
"	4-32	1	1940	6	1600	No bounce or chop.
"	4-33	1	1940	6	1600	No bounce or chop.

Table III - continued

Development Forging Parameters for Spiral Bevel Gear (44 Teeth)

Forging Conditions

Forging Operation	Forging No. Lot-Pc.	No. of Hits	Furn. Temp. °F	Stroke Height in.	Firing Pressure psi	Notations
Finish (31 pcs)	4-34	1	1940	6	1600	No bounce or chop.
"	4-36	1	1940	6	1600	No bounce or chop.
						Time intervals for finish forging operation: a. Furnace heating of block pcs: 14 ± 2 min. b. Transfer from furnace to die and hit: 15 ± 5 sec. c. Ejection from die: 25 ± 5 sec.

The major portion of the gear forging development effort involved the finish forging process for establishing suitable forging conditions to produce completely filled forgings repeatedly and without sustaining secondary damage to the forged tooth elements by bounce or ejection procedures.

The tooth sections of the first of six parts processed through the second finish forge development run, were completely filled with one hit at 1775° F, 1200 psi firing pressure and 12" stroke. Incomplete tooth section filling was encountered with the next four pieces. Multiple reheats, hits and incremental increases to the forging force were necessary to complete the tooth section fill. The sixth piece was finish forged satisfactorily with one hit at 1775° F, 1400 psi and 16" stroke. Detail dimensional and grind inspection of three forgings from this group (2-2, 2-4, 2-6) were performed and the results are presented in Section 4.

A high percentage of tooth damage was experienced, due to bounce and chop. After the forging punch impacts the work piece, it will bounce several times before arresting. During this interval, if the forged gear is dislodged and becomes cross threaded in the die cavity, the returning impact by the punch will result in gross damage to the forged tooth section, otherwise known as "chopping". Evidence of local deformation to the ends of the die tooth elements at the parting face were noted in the fore part of the forging run. This condition continued to progress rapidly to the point where the feathered end surface of the tooth element had bent inwardly to cause a locked thread effect on the forged spiral teeth at the heel end of the gear, thus making ejection difficult and causing face damage to a portion of the convex profile of the forged teeth upon removal from the die. This condition was temporarily eliminated by a .030" facing cut and chamfering the feather edge of the die tooth elements on the concave profile side. The results of the finish forging development run indicated that the combination of forging conditions to be marginal for consistently providing tooth section filling and for that reason a higher set of forge conditions (2000° F, 1800 psi firing pressure and 18" stroke) were selected for try-out. These conditions proved to be excessive as evidenced by complete longitudinal fracture of the die body.

Durodi, Temper I (R_c42-46) was used for the replacement gear-finishing die. Preparation was in the same manner as used for the original die except a corrective revision was made to the EDM in-feed guide helix in accordance with inspection information from the original gear forgings. The feathered edges of the die tooth forms at the parting face were chamfered.

Upon completion of the replacement die, the gear finish forging development was resumed, employing relatively conservative forge conditions which were gradually adjusted to the final condition of 1950° F, 1600 psi firing pressure and

6" stroke. Principal forging difficulties encountered were inconsistent tooth section filling at the toe end, part bounce and chop damaged teeth. Also, progressive deformation occurred to the die tooth segment adjacent to the parting face (Figure 14). A typical example of the hardware from billet to finish forging resulting from the gear development forging effort, is illustrated in Figure 15.

Spiral Bevel Pinion Forging

The initial twenty piece developmental forging run of the shank shaft spiral bevel pinion resulted in gross damage to both the block and finish dies. The type and location was the same as that which occurred in the 44 tooth gear dies. The deformation was greater in magnitude and developed earlier. Several teeth had segments broken off. The damaged block die is shown in Figure 16.

Rework of the dies incorporated a corrective redesign that provided a 45° chamfered collar to the die tooth segment and the addition of a flash gutter as shown in Figure 17. Follow-on development and preproduction forging runs demonstrated that the revised design provided a major beneficial effect in prolonging the die life, but did not eliminate the basic problem.

In continuing the pinion forging development, three series of forging runs were made in lot sizes of ten to twenty pieces for establishing suitable combination of billet and preform sizes, preform shape and forging parameters for the preform, block and finish operations, and are described in Table IV. Series of adjustments to the pinion preform shape were necessary to provide for an improved preferential grain flow in the block forging and complete tooth section fill. The preform shape evolution is shown in Figure 18.

During the various phases of the forge development, routine macro-examinations were made for forging flow characteristics and for detection of forging defects. In addition to making trial checks on AMS 6265 forged material, samples of AISI 1018 were included to facilitate the macro etch development of the forging flow lines.

Figure 14. Deformation of the Gear Die Spiral Bevel Teeth

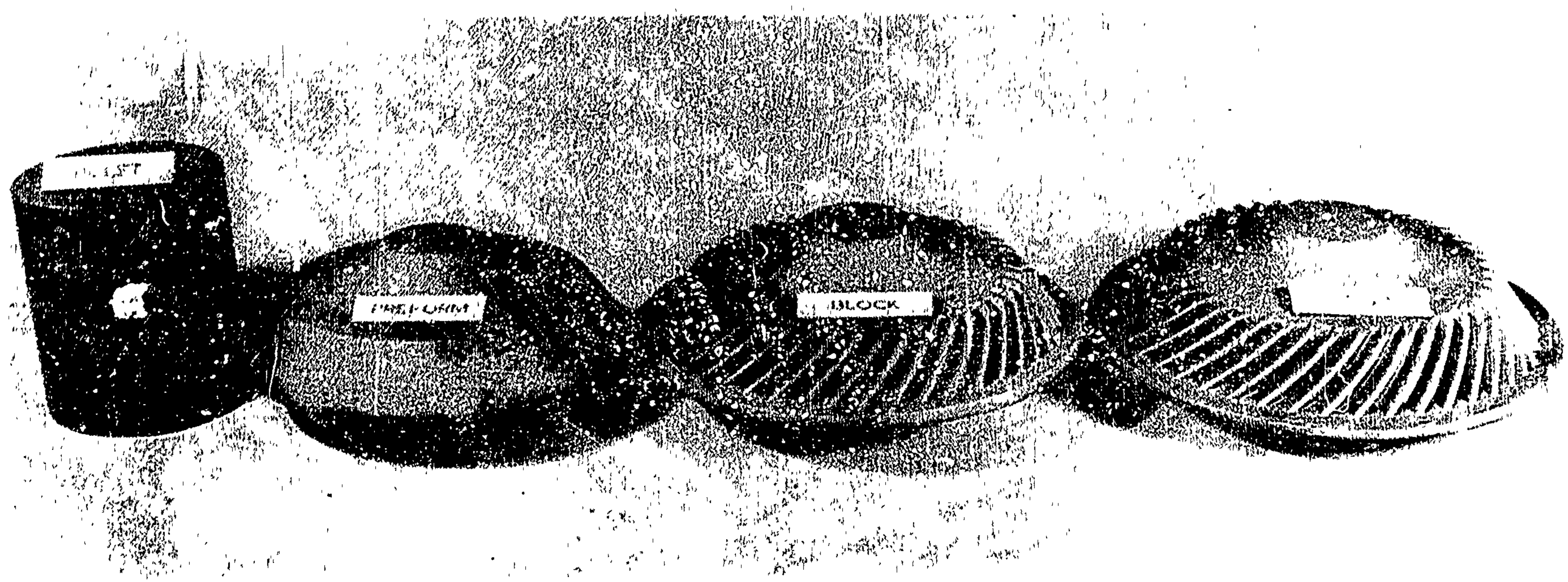


Figure 15. High Velocity Forge Staging Sequence Used for the Spiral Bevel Gear

Figure 16. Damaged Pinion Block Die

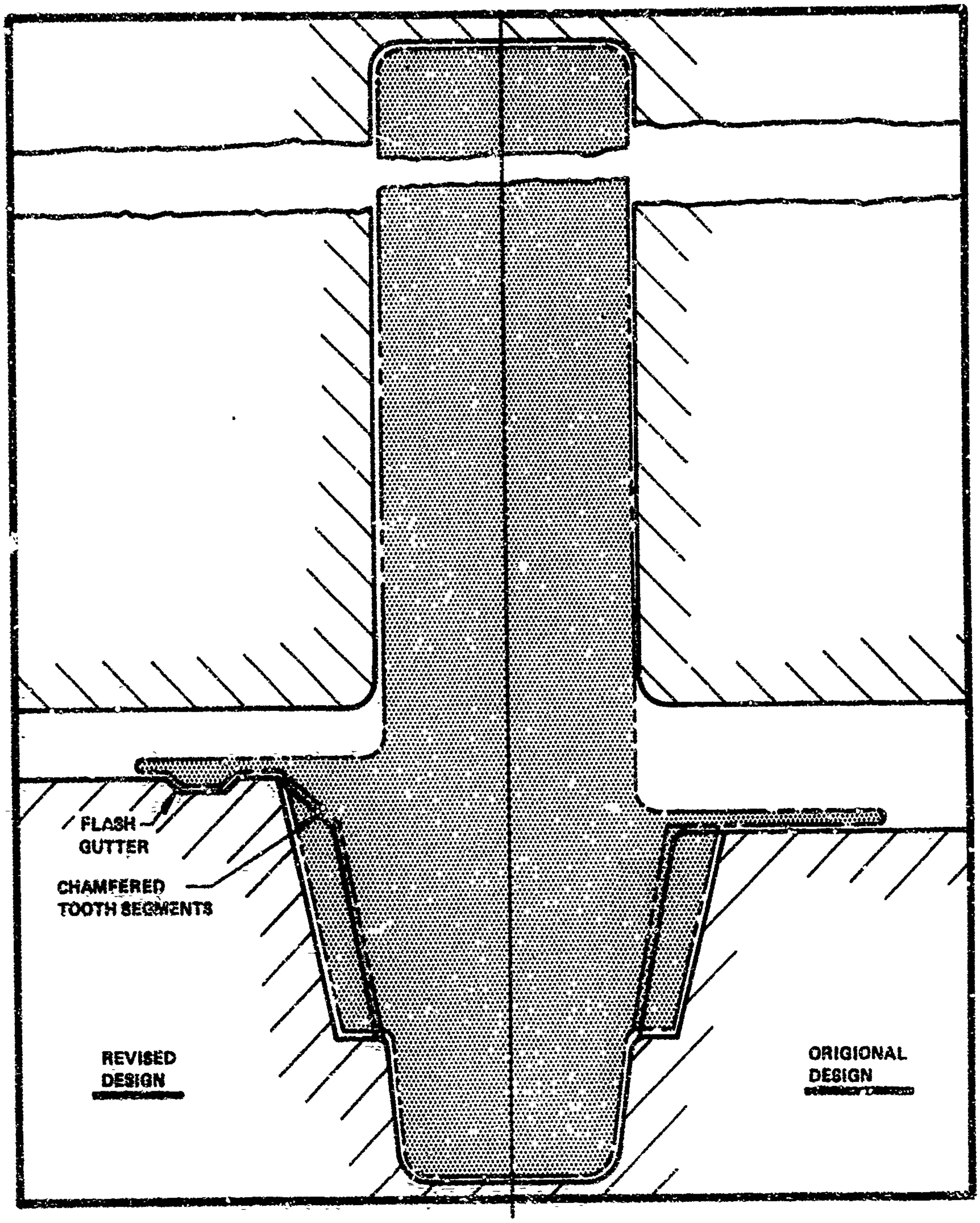


Figure 17. Original and Revised Design of the Spiral Bevel Pinion Block and Finish Dies

Table IV

Development Forging Parameters for Spiral Bevel Pinion (15 Teeth)

Forging Conditions

Forging Operation	Forging No. Lot-Pc.	No. of Hits	Furn. Temp. °F	Stroke Height in.	Firing Pressure psi	Notations
Preform (20 pcs)	1-1 to 1-20	1	1950	13	1200	Billets: AMS 6265; 1-3/4" round by 16" long.
Block (20 pcs)	1-1 to 1-6	1	1950	12	1200	Tooth section at toe end not completely filled; rough forge surface on tooth top land. To improve the rough condition, a .030" clean-up cut was made on the cone area of the balance of the preform forgings.
	1-7 to 1-14	1	2050	12	1100	Tooth toe end not completely filled. Good surface finish on top land. Die tooth form adjacent to parting face showed evidence of progressively deforming in an upward and outward direction.
	1-15 to 1-20	1	1800	12	1200	Tooth fill at toe end did not improve. Die teeth continued to deform by bending (rolling) at the ends; several teeth had segments broken off.
Finish (15 pcs)	1-1 to 1-15	1	1800	9-11	1000 -1200	Tooth sections at toe end not completely filled.

Table IV - continued

Development Forging Parameters for Spiral Bevel Pinion (15 Teeth)

Forging Conditions

Forging Operation	Forging No. Lot-Pc.	No. of Hits	Furn. Temp. °F	Stroke Height in.	Firing Pressure psi	Notations
Finish (15 pcs)						Progressive bending deformation of die tooth form occurred in region adjacent to parting face. Deformation was similar to blocker, except in opposite direction - inward & downward from parting face.
Preform (20 pcs)	2-1 to 2-15 2-16 to 2-20	1 1	1850 1850	14 14	1200 1200	Billets for 2-1 to 2-15: AMS 6265; 1-3/4" round by 16" long. Billets for 2-16 to 2-20: AISI 1018; 1-3/4" round by 16" long.
Block (Redesign Die) (20 pcs)	2-1 to 2-20	1	1900	12	1200	"Blocked" tooth section did not fill; attributed to insufficient material in preform.
Finish (Redesign Die) (10 pcs)	2-1 to 2-5 and 2-15 to 2-20	1	1850	9	1000	Tooth sections did not fill. Corrective Action: 1. Billet length increased 3/4". 2. Length of cone section of preform increased 1-1/16".

Table IV - continued

Development Forging Parameters for Spiral Bevel Pinion (15 Teeth)

Forging Conditions

Forging Operation	Forging No. Lot-Pc.	No. of Hits	Furn. Temp. °F	Stroke Height in.	Pressure psi	Notations
Preform (10 pcs)	3-1 to 3-10	1	1850	14	1200	Billets: AMS 6265; 1-3/4" round by 16-3/4" long.
Block (9 pcs)	3-1 to 3-9	1	1850/ 1900	12	1200	Tooth sections filled.
Finish (8 pcs)	3-1 to 3-8	1	1800/ 1850	8-9	1000	Tooth section did not completely fill at toe end. Corrective Action: Length of stub shaft section in blocked die increased an additional 0.5".
Preform (19 pcs)	4-1 to 4-19	1	1800/ 1850	12	1000	Billets for 4-1 to 4-12: AMS 6265; 1-3/4" round by 16-3/4" long Billets for 4-13 to 4-19: AISI 1018; 1-3/4" round by 16-3/4" long.
Block (17 pcs)	4-1 to 4-11 4-13 to 4-18	1	1800/ 1850	12	1600	

Table IV - continued

Development Forging Parameters for Spiral Bevel Pinion (15 Teeth)

Forging Conditions

Forging Operation	Forging No. Lot-No.	No. of Hits	Furn. Temp. °F	Stroke Height in.	Firing Pressure psi	Notations
Finish (15 pcs)	4-1 to 4-10 4-13 to 4-17	1	1800/ 1850	11	1200	First piece forged indicated that the 1/2" addition was excessive. Removal of 3/8" from 2nd piece did not leave enough material. 1/4" trim (1-1/8" stub shaft length) provided the correct amount of material as evidenced by degree of tooth filling.

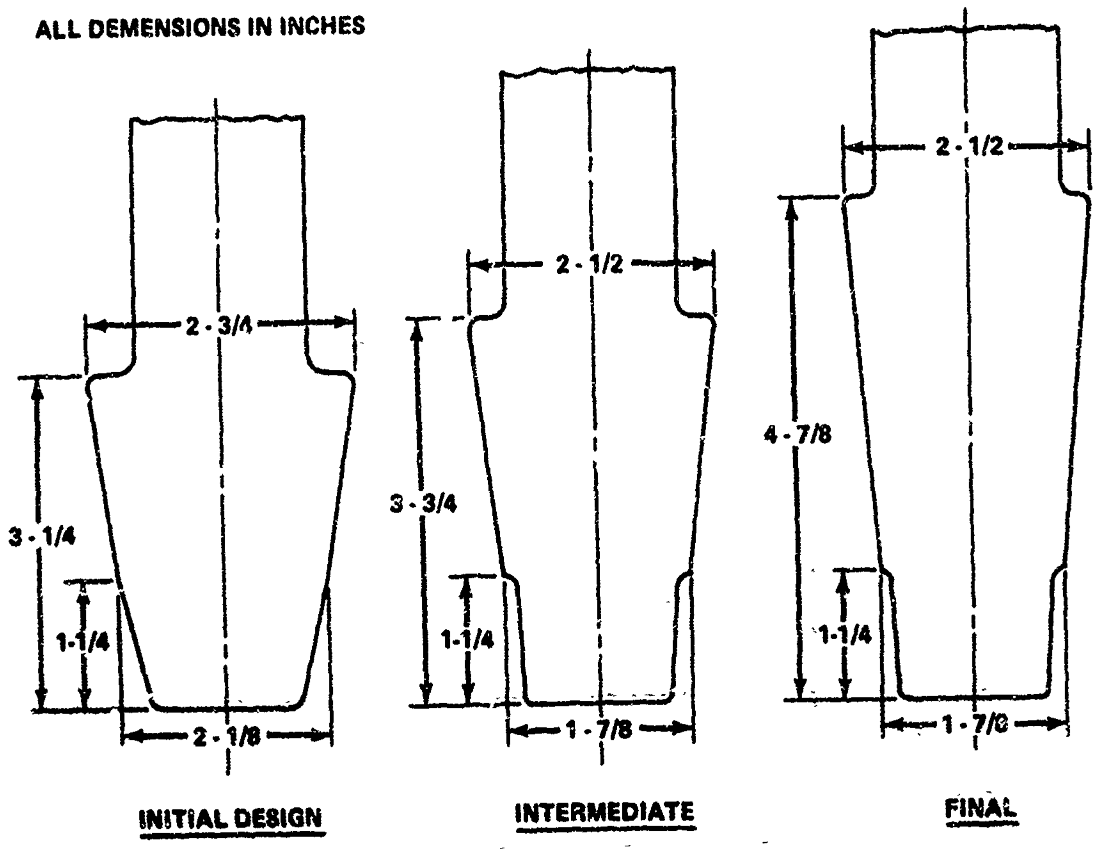


Figure 18. Progressive Development of Pinion Preform Forging

PHASE II - PREPRODUCTION FORGING

Pinion Preproduction Forging

A preproduction lot of sixty-three spiral bevel pinions were forged by the procedures established by the development effort and with additional refinements as required. Description of the forging conditions and other pertinent information is presented in Table V. Examples of the preproduction forged hardware, from billet to finish forging are illustrated in Figure 19.

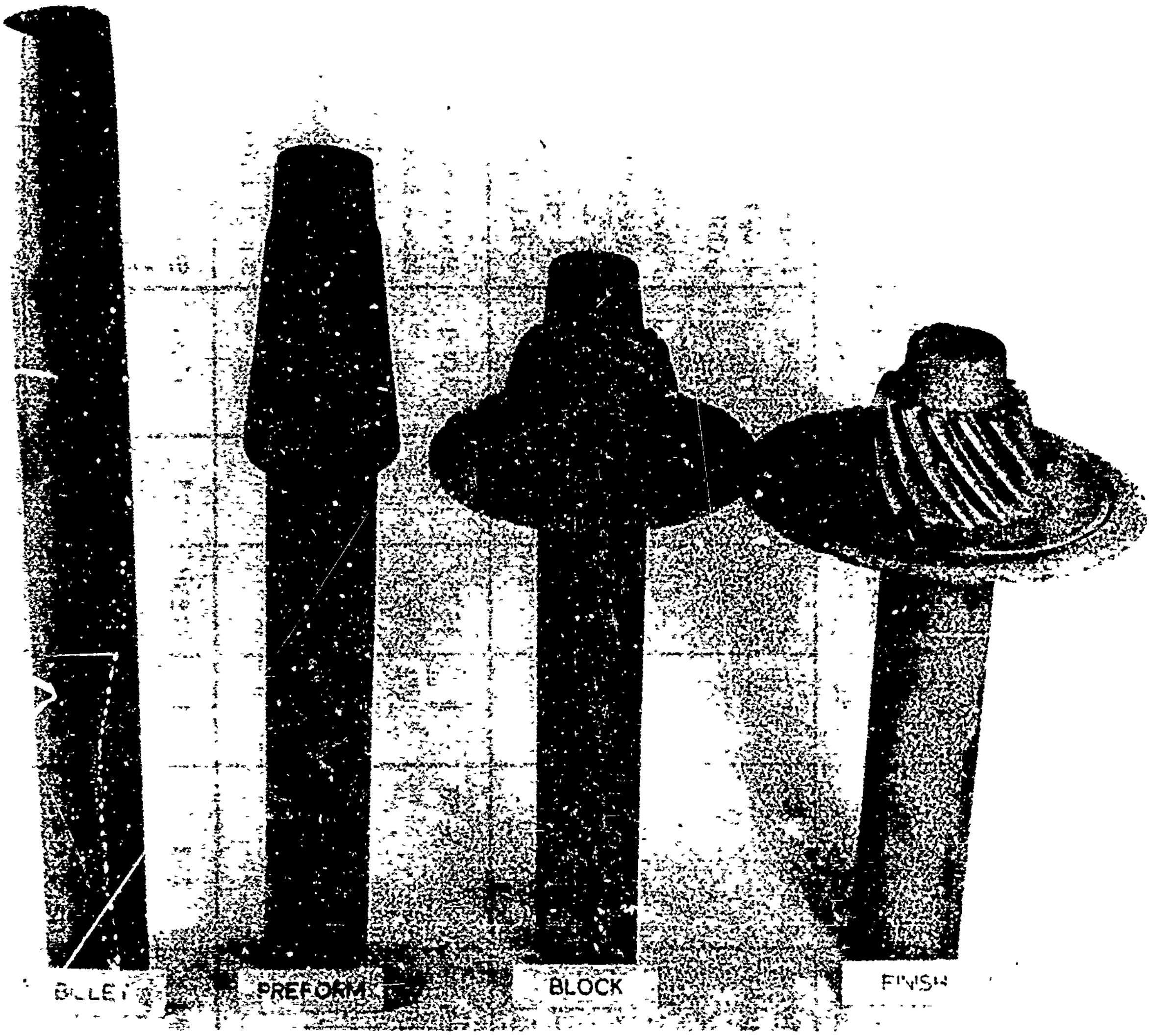


Figure 19. High Velocity Forge Staging Sequence Used For The Spiral Bevel Pinion

Table V
Preproduction Forging Parameters for Spiral Bevel Pinion (15 Teeth)

Forging Conditions

Forging Operation	Forging No. Lot-Pc.	No. of Hits	Furn. Temp. °F	Stroke Height in.	Firing Pressure psi	Notations
Preform (63 pcs)	5-1 to 5-63	1	1825/ 1875	12	1200	Billets: Abrasive cut 16-3/4" long pcs. from 1-3/4" round mill length bars of AISI 9310 (AMS 6265) deburred & abrasive cleaned. Furnace atmosphere: Gas rich. Lubricant: Oil & graphite applied by swab dabbing die & punch cavities, followed by air blasting. Forging Time Interval: 5-10 seconds from furnace to hit; 45-60 seconds per preform cycle.
Block (63 pcs)	5-1 to 5-63	1	1825/ 1875	12	1600	Preforms were cleaned, inspected and cone surfaces hand ground to remove slight surface imperfections. Furnace atmosphere: Gas rich. Lubricant: Oil & graphite applied by swab dabbing and uniformly dispersed by air blasting.
Finish (63 pcs)	5-1	1	1850	11	1200	Stub shaft length of block forgings shortened to 1-1/8" by lathe turning.

Table V - continued

Preproduction Forging Parameters for Spiral Bevel Pinion (15 Teeth)

Forging Conditions

Forging Operation	Forging No. Lot-Pc.	No. of Hits	Furn. Temp. °F	Stroke Height in.	Firing Pressure psi	Notations
Finish (63 pcs)						Blocked pcs. were abrasive cleaned & magnafluxed; all indications were removed by hand burring & were found to be due to superficial surface defects.
						Starting die temp. 175°F. Lubricant: Oil & graphite lightly dabbed and uniformly dispersed by air blasting. Part ejected along with punch. Fill & appearance good.
	5-2	1	1850	11	1200	Part bounced. Depth of locking hooks in die were increased by hand grinding.
	5-3	1	1850	11	1200	Part stayed in die - no bounce.
	5-4 to 5-7	1	1850	11	1200	Appearance satisfactory.
	5-8 to 5-9	1	1850	11	1200	No lubricant used; appearance satisfactory.
	5-10 to 5-24	1	1850	11	1200	Normal lubrication used. Die temp. 250°F. General appearance good except toe end of tooth not completely filled; difficult to eject from die; water flooding of die used frequently to assist ejection.

Table V - continued

Preproduction Forging Parameters for Spiral Bev. inion (15 Teeth)

Forging Conditions

Forging Operation	Forging No. Lot-Pc.	No. of Hits	Furn. Temp. °F	Stroke Height in.	Firing Pressure psi	Notations
Finish (63 pcs)	5-25	1	1850	11	1200	Die temp. 225° F.
	5-26	1	1850	11	1200	No lube used; part satisfactory; ejected easily.
	5-27	1	1850	11	1200	No lube; stuck in die & flooded with water to assist ejection.
	5-28 & 5-29	1	1850	11	1200	Dry graphite lube; ejected freely.
	5-30	1	1850	11	1200	Ditto lube; stuck; water flooding, 3 min. to remove.
	5-31 & 5-32	1	1850	11	1200	Oil & graphite lube; ejected freely. Die inspection: Top of teeth at heel end (adjacent to die face) showed evidence of rolling.
	5-33 to 5-52	1	1850	11	1200	Small variations were made to lubricant quantity & degree of dispersion; had an observed effect on part ejection. Additional roll (bend) deformation of die teeth noted.
	5-53 to 5-57	1	1800	11	1200	Lubrication method for balance of run consisted of using graphite & oil lightly dabbed into the cavity, then uniformly distributed into each tooth segment by air blasting.

Table V - continued
Preproduction Forging Parameters for Spiral Bevel Pinion (15 Teeth)

Forging Conditions

Forging Operation	Forging No. Lot-Pc.	No. of Hits	Temp. °F	Stroke Height in.	Firing Pressure psi	Notations
Finish (63 pcs)	5-58 to 5-63	1	1850/ 1875	11	1200	All pieces filled satisfactorily, and all except one ejected freely.

RESULTS AND DISCUSSION

Inspection and Evaluation of Forged Gears and Pinions

In conjunction with the forging process development, standard gear inspections and grind stock removal evaluations were performed on sample forgings to obtain data for checking the following characteristics:

a. Accuracy of the EDM method for generating a spiral bevel gear die cavity from a known gear electrode geometry;

b. Allowances made for shrinkage and EDM spark gap;

c. Tooth thickness variation resulting from the forging process;

d. Variation of stock removal along the convex and concave profile surfaces of the gear teeth during the final grinding operation.

In order to perform the inspection operations, it was necessary to machine the forging so that it could be fixtured in one or more of the inspection facilities. In machining the forging, it was chucked in a spindle and indicated for run-out on the front face of the cone and on the outside diameter of the gear. Centers were then established and the flash was removed. The forgings were bored and machined to correct blank geometry.

A condensation of pertinent gear and pinion inspection data is provided in Tables VI to IX. The following processed data from Table VI shows that good correlation was obtained for the shrink allowance factor of .0125"/" used in design of the EDM electrodes and die cavity.

$$\begin{bmatrix}\text{Electrode}\\ \text{avg. dia.}\\ \end{bmatrix} + \begin{bmatrix}\text{Spark gap}\\ \text{allowance}\\ \text{(.002"/side)}\end{bmatrix} = \begin{bmatrix}\text{Die cavity}\\ \text{dia.}\\ \end{bmatrix} - \begin{bmatrix}\text{Shrink}\\ \text{allowance}\\ \text{(.0125"/")}\end{bmatrix} = \begin{bmatrix}\text{Forging}\\ \text{dia.}\\ \end{bmatrix}$$

$$8.258" + .004" = 8.262" - 8.262" \times .0125 = \underline{8.1587"}$$

$$\text{Avg. dia. of forging by inspection} = \underline{8.159"}$$

The diameter of the Cerro alloy proof cast (8.264") provided a close check within inspection accuracy, with the above calculated die diameter (8.262").

Table VI
Spiral Bevel Gear Measurement Data

Position Location	(A) (Inches) Outside Diameter & Intersection of Heel & Flange	(B) (Inches) Axial Length From Flange to Toe Face	(C) (Inches) Axial Length From Flange to Toe Hub End
	Brass Electrode #9 Used to Finish Replacement Die		
1-3	8.258	(1) 1.325	(1) 2.228
		(2) 1.324	(2) 2.226
2-4	8.259	(3) 1.324	(3) 2.225
		(4) 1.325	(4) 2.227
	Avg. 8.258	Avg. 1.324	Avg. 2.226
	Casting From Replacement Finishing Die		
1-3	8.264		(1) 2.216
		(2) 1.325	(2) 2.231
2-4	8.263		(3) 2.233
			(4) 2.228
	Avg. 8.263	Avg. 1.325	Avg. 2.227
	Finish Forged Gear #4-36 From Replacement Die		
1-3	8.161	(1) 1.314	(1) 2.221
		(2) 1.299	(2) 2.206
2-4	8.157	(3) 1.316	(3) 2.226
		(4) 1.310	(4) 2.221
	Avg. 8.159	Avg. 1.310	Avg. 2.218

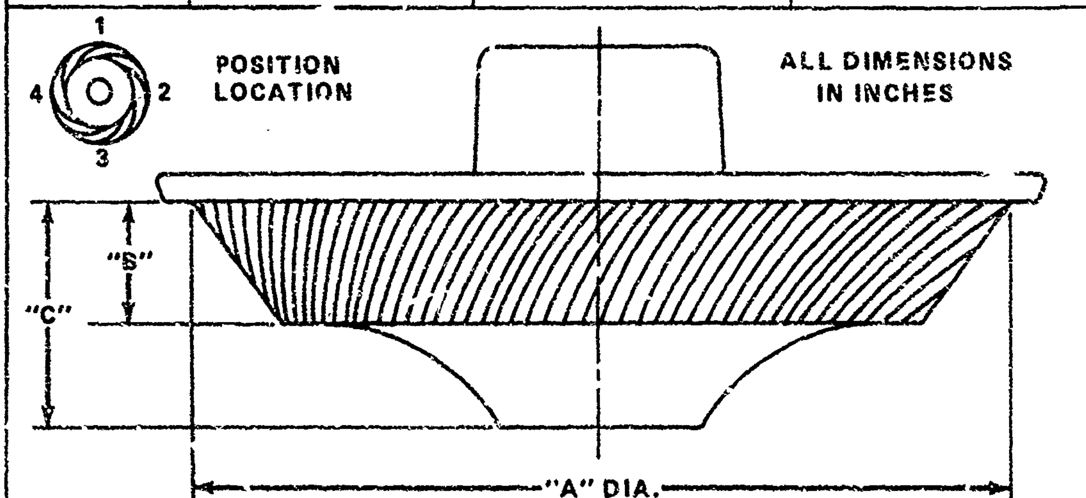


Table VII
Gear Tooth Thickness Measurements

Identification	Toe (Inches) Add. .060	Toe (Inches) Add. .225	Center (Inches) Add. .060	Center (Inches) Add. .225	Heel (Inches) Add. .060	Heel (Inches) Add. .225
Frg. #2-2	.148	.250	.148	.256	.145	.254
	.151	.254	.151	.259	.148	.256
	.153	.255	.150	.256	.148	.253
	.148	.251	.147	.255	.143	.251
Avg.	.150	.252	.149	.256	.146	.254
Variation	.005	.005	.004	.004	.005	.005
Frg. #2-4	.152	.254	.153	.256	.149	.257
	.151	.254	.148	.257	.145	.251
	.148	.252	.144	.255	.143	.253
	.147	.251	.147	.256	.147	.257
Avg.	.150	.253	.148	.256	.146	.254
Variation	.005	.003	.009	.003	.006	.006
Frg. #2-6	.147	.251	.147	.256	.145	.255
	.148	.252	.149	.258	.147	.255
	.152	.256	.152	.259	.148	.255
	.149	.253	.148	.255	.143	.255
Avg.	.149	.253	.149	.257	.148	.255
Variation	.005	.005	.005	.004	.005	.000
Combined Range	.147	.250	.144	.255	.143	.251
	.153	.256	.153	.259	.149	.257
Combined Variation	.006	.006	.009	.004	.006	.006
Nominal Finished Gear Tooth Thickness	.124	.230	.125	.232	.126	.235

Above data obtained from forging produced in original finishing die (before breakage).

Table VII - continued
Gear Tooth Thickness Measurements

Identification	Toe (Inches)		Center (Inches)		Heel (Inches)	
	Add. .060	Add. .225	Add. .060	Add. .225	Add. .060	Add. .225
Electrode #9	.148	.250	.149	.255	.145	.256
(Used to finish	.147	.249	.150	.254	.145	.255
die)	.148	.251	.150	.255	.146	.255
	.147	.250	.149	.255	.146	.256
Avg.	.148	.250	.150	.255	.146	.256
Variation	.001	.002	.001	.001	.001	.001
Casting	.157	.263	.158	.265	.159	.268
(of die before	.160	.271	.164	.271	.161	.272
use)	.160	.268	.164	.272	.162	.273
	.158	.269	.160	.274	.161	.279
Avg.	.159	.268	.162	.270	.161	.273
Variation	.003	.008	.006	.009	.003	.011
Frg. #4-13			.164	.266		
			.162	.265		
			.158	.264		
			.160	.264		
Avg.			.161	.265		
Variation			.006	.002		
Frg. #4-26			.160	.266		
			.162	.264		
			.161	.262		
			.159	.262		
Avg.			.160	.264		
Variation			.003	.004		
Frg. #4-36	.159	.266	.161	.270	.161	.259
	.161	.266	.164	.272	.163	.258
	.159	.266	.160	.268	.158	.260
	.156	.265	.158	.269	.159	.265
Avg.	.15[illegible]	.266	.161	.270	.160	.260
Variation	.005	.001	.006	.004	.005	.007

Above date is for the replacement die.

Table VIII
Pinion Tooth Thickness Measurements

Identification	Toe (Inches) Addendum .195	1.187 From Toe (Inches) Addendum .195
Electrode	.273	.277
	.272	.278
	.272	.278
Avg.	.272	.278
Variation	.001	.001
#1 Casting	.277	.283
(from finishing die	.275	.282
after EDM)	.276	.283
Avg.	.276	.283
Variation	.002	.001
#2 Casting	.275	.281
(from finishing die	.274	.282
before use)	.275	.281
Avg.	.275	.281
Variation	.001	.001
Frg. #4-10	.280	.284
(development frg.)	.277	.282
	.277	.281
Avg.	.278	.282
Variation	.003	.003
Frg. #4-15	.275	.280
(development frg.)	.277	.281
	.273	.283
Avg.	.275	.281
Variation	.004	.003
#3 Casting	.27[illegible]	.283
(finishing die after	.274	.282
forging 33 development)	.274	.284
frgs.)		
Avg.	.274	.283
Variation	.000	.002

Table VIII - continued
Pinion Tooth Thickness Measurements

Identification	Toe (Inches) Addendum .195	1.187 From Toe (Inches) Addendum .195
Preproduction Forgings		
Frg. #5-1	.274	.280
5-2	.273	.281
5-4	.274	.283
5-7	.274	.282
5-9	.274	.282
5-10	.274	.281
5-11	.271	.281
5-18	.273	.278
5-20	.270	.280
Avg.	.273	.281
5-26	.273	.280
5-29	.271	.280
5-30	.273	.277
5-35	.270	.277
5-39	.266	.280
Avg.	.270	.279
5-41	.266	.277
5-42	.269	.279
5-44	.269	.281
5-48	.272	.278
5-49	.266	.280
5-52	.271	.276
5-55	.271	.276
5-56	.264	.277
5-58	.269	.279
5-59	.267	.277
5-60	.267	.280
Avg.	.268	.278

Table VIII - continued
Pinion Tooth Thickness Measurements

Identification	Toe (Inches) Addendum .195	1.187 From Toe (Inches) Addendum .195
Combined tooth thickness range of 25 frgs. from 63 pc. pre-production forge lot	.264 .274	.276 .283
Total variation of lot	.010	.007
#4 Casting (from finishing die after forging 96 pcs.)	.269 .271 .270	.277 .280 .281
Avg.	.270	.279
Variation	.002	.004

Table IX
Preproduction Pinion Tooth Thickness As-Forged

Forging No.	Toe (Inches) Add. .040	Add. .235	Center (Inches) Add. .040	Add. .235	Heel (Inches) Add. .040	Add. .235
5-1	.158	.293	.158	.298	.149	.302
	.158	.293	.157	.299	.151	.300
	.157	.291	.157	.299	.151	.301
	.157	.290	.156	.298	.150	.299
	.157	.292	.157	.298	.151	.301
	.157	.293	.159	.30[illegible]	.150	.302
	.158	.293	.158	.300	.149	.299
	.158	.292	.157	.298	.149	.300
	.158	.293	.157	.299	.150	.299
	.158	.294	.156	.301	.147	.299
	.158	.294	.157	.302	.151	.303
	.158	.295	.158	.302	.150	.304
	.160	.296	.159	.302	.151	.303
	.159	.294	.158	.303	.150	.301
	.158	.294	.157	.300	.149	.301
Avg.	.158	.293	.157	.300	.150	.301
Variation	.003	.006	.003	.005	.004	.005
5-4	.156	.291	.157	.298	.154	.301
	.156	.293	.157	.298	.153	.3[illegible]
	.157	.294	.157	.299	.155	.3[illegible]
Avg.	.156	.293	.157	.298	.154	.301
Variation	.001	.003	.000	.001	.002	[illegible]
5-10	.157	.292	.158	.301	.155	.3[illegible]
	.159	.290	.157	.299	.153	.300
	.158	.293	.158	.300	.155	.300
Avg.	.158	.292	.158	.300	.154	.300
Variation	.002	.003	.001	.002	.002	.00[illegible]
5-29	.158	.290	.158	.298	.154	.299
	.156	.288	.157	.298	.154	.300
	.158	.286	.156	.297	[illegible]	.299
	.156	.287	.156	.295	.153	.298
	.157	.290	.157	.296	.154	.299
	.158	.290	.156	.296	.154	.300
	.158	.290	.157	.297	.155	.300

Table IX - continued
Preproduction Pinion Tooth Thickness As-Forged

Forging No.	Toe (Inches) Add. .040	Toe (Inches) Add. .235	Center (Inches) Add. .040	Center (Inches) Add. .235	Heel (Inches) Add. .040	Heel (Inches) Add. .235
5-29 con't	.158	.290	.158	.295	.155	.300
	.159	.287	.158	.296	.154	.300
	.158	.289	.159	.295	.155	.298
	.159	.290	.158	.296	.155	.297
	.160	.291	.159	.296	.155	.297
	.160	.290	.160	.297	.155	.297
	.159	.292	.158	.298	.155	.300
	.157	.290	.157	.296	.154	.298
Avg.	.158	.289	.158	.296	.154	.299
Variation	.004	.006	.004	.003	.002	.003
5-56	.157	.288	.157	.294	.155	.295
	.155	.287	.157	.293	.156	.297
	.155	.289	.158	.292	.155	.296
Avg.	.156	.288	.157	.293	.155	.296
Variation	.002	.002	.001	.002	.001	.002
5-60	.158	.290	.158	.291	.155	.293
	.157	.290	.157	.290	.156	.290
	.158	.289	.158	.291	.156	.292
	.157	.290	.157	.291	.154	.293
	.157	.290	.157	.294	.155	.293
	.157	.290	.157	.293	.156	.294
	.158	.289	.157	.293	.156	.294
	.158	.289	.157	.293	.156	.295
	.158	.290	.158	.293	.156	.297
	.159	.289	.158	.292	.155	.297
	.159	.288	.158	.293	.157	.296
	.159	.288	.159	.293	.157	.298
	.160	.290	.159	.293	.157	.296
	.160	.289	.159	.293	.157	.297
	.158	.288	.158	.292	.155	.294
Avg.	.158	.289	.158	.292	.156	.295
Variation	.003	.002	.002	.004	.003	.008

Table IX continued
Preproduction Pinion Tooth Thickness As Forged

Forging No.	Toe (Inches) Add. .040	Toe (Inches) Add. .235	Center (Inches) Add. .040	Center (Inches) Add. .235	Heel (Inches) Add. .040	Heel (Inches) Add. .235
Average for six piece sample lot from 63 pc. preproduction forging run	Lot Range					
	.155 / .160	.286 / .296	.156 / .160	.290 / .303	.147 / .157	.290 / .304
	Lot Variation					
	.005	.010	.004	.013	.010	.014
Nominal Finished Gear Tooth Thickness	.134	.265	.138	.279	.14[illegible]	.284

Electrode tooth thickness at two locations, corrected for spark gap, provided reference dimensions to compare and determine the efficacy if the forged tooth size (thickness) was equivalent to a generated cut tooth (suitable for final grinding). As an example, the two pinion electrode references from Table VIII were .272" and .278" at the toe and heel locations, respectively. When corrected for spark gap became .276" and .282", which correlates quite closely with the two die cavity casts (.275", .276" and .281", .283"). In general, the pinion forging measurements compared favorably with the above references, indicating a dimensionally satisfactory forged [illegible] with regard to tooth thickness.

The maximum variation that occurred in the combined tooth measurements of all gears and pinions inspected was .009" and .014", respectively. The maximum tooth thickness variation for an individual forging was [illegible], with .004" maximum being representative of the majority of individual forgings inspected.

The pinion average tooth thickness data from Tables VIII and IX are graphically presented in Figure 20, which shows the effect of die usage on the resultant forged tooth thickness. It will be noted that the average forged thickness at the large addendum location decreased approximately .005" to .007" from the beginning to the end of the forging run, whereas no appreciable change occurred at the .040 addendum location. These data indicate the progressive

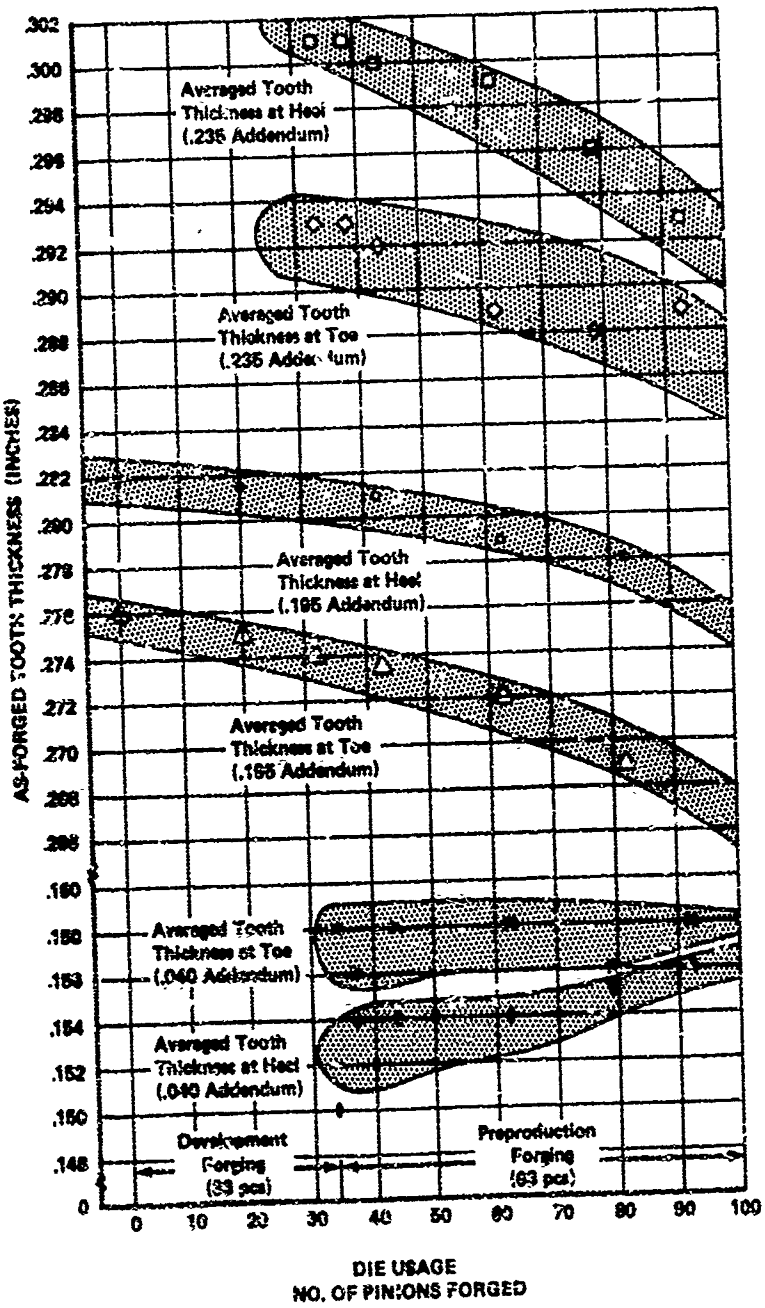


Figure 20. Effect of Die Usage on Pinion Tooth Thickness

mode of up-set deformation that occurred to the die tooth profile and is illustrated schematically in Figure 21.

Forged tooth thickness data provide only an indication that a tooth has been correctly produced. In order to determine the amount and distribution of the excess material on each tooth face, it was necessary to progressively grind (per applicable spiral bevel schedules) in known incremental steps and maintain a topographical record of the amount and location of the stock removed. A partial series of these recordings is shown in Figure 22.

This evaluation was performed for two conditions; (1) as-forged and (2) carburized and hardened. In the production of conventionally machined spiral bevel gears, a spiral angle adjustment during the carburizing and hardening cycle makes it necessary to bias the spiral bevel gear generator to compensate for the heat treating distortion. The electrodes for the spiral bevel dies were machined to this biased setting; but it was not known whether or not the precision forged spiral geometry would react to the same degree as the conventionally manufactured gears. The grind stock conditions (Table X) indicated that the spiral angle of the precision forged gear does tend to adjust in a manner similar to that of a cut and heat treated gear, however, considerably more evaluation data would be required to establish the quantitative similarity of the spiral unwind. The average total amount of stock that had to be removed to obtain finish grind size varied from a minimum of .016"/.022" to a maximum of .029"/.034" for the two as-forged gears, and .016" minimum to .026" maximum for the heat treated gear.

A six piece sample lot of preproduction forged pinions were carburized, heat treated and ground for stock removal evaluation. Due to an electrode machining error that caused a shallow tooth root to be produced in the forging, the evaluation was limited to a clean-up grind of both tooth faces, the results of which are graphically presented in Figure 23.

Metallurgical Evaluation

Metallurgical surveillance of the forging process was maintained throughout the development program, including examination and tests of representative samples for forging quality and flow characteristics. All forged pieces were nondestructively tested and indications were evaluated for their nature and extent. No major forging flaws were encountered. Macro etch preparation and examinations were made of sectioned forgings and tooth elements (Figures 24 to 27).

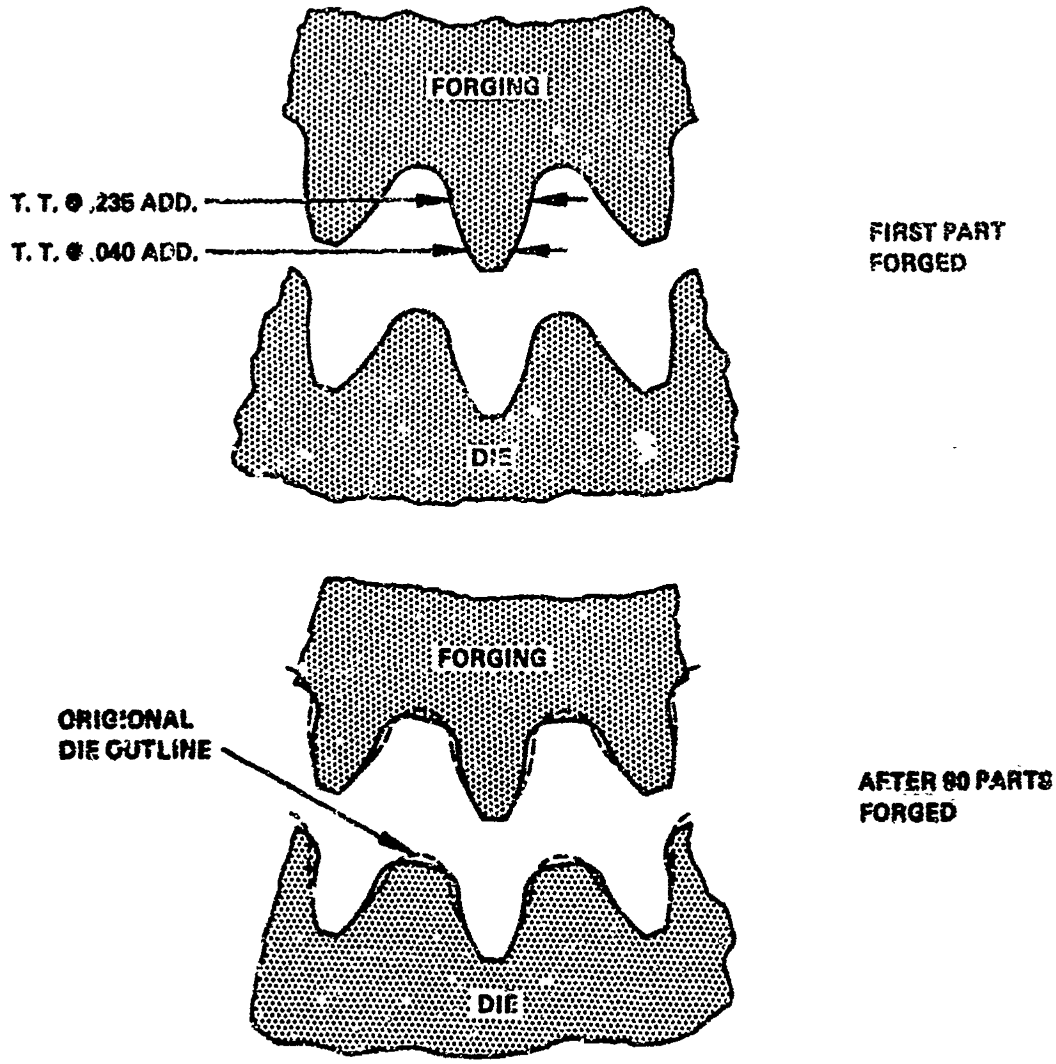


Figure 21. Transverse Section Through Die Tooth Element and Forged Tooth Showing the Up-set Die Tooth and the Resulting Effect on the Forged Pinion Tooth Geometry

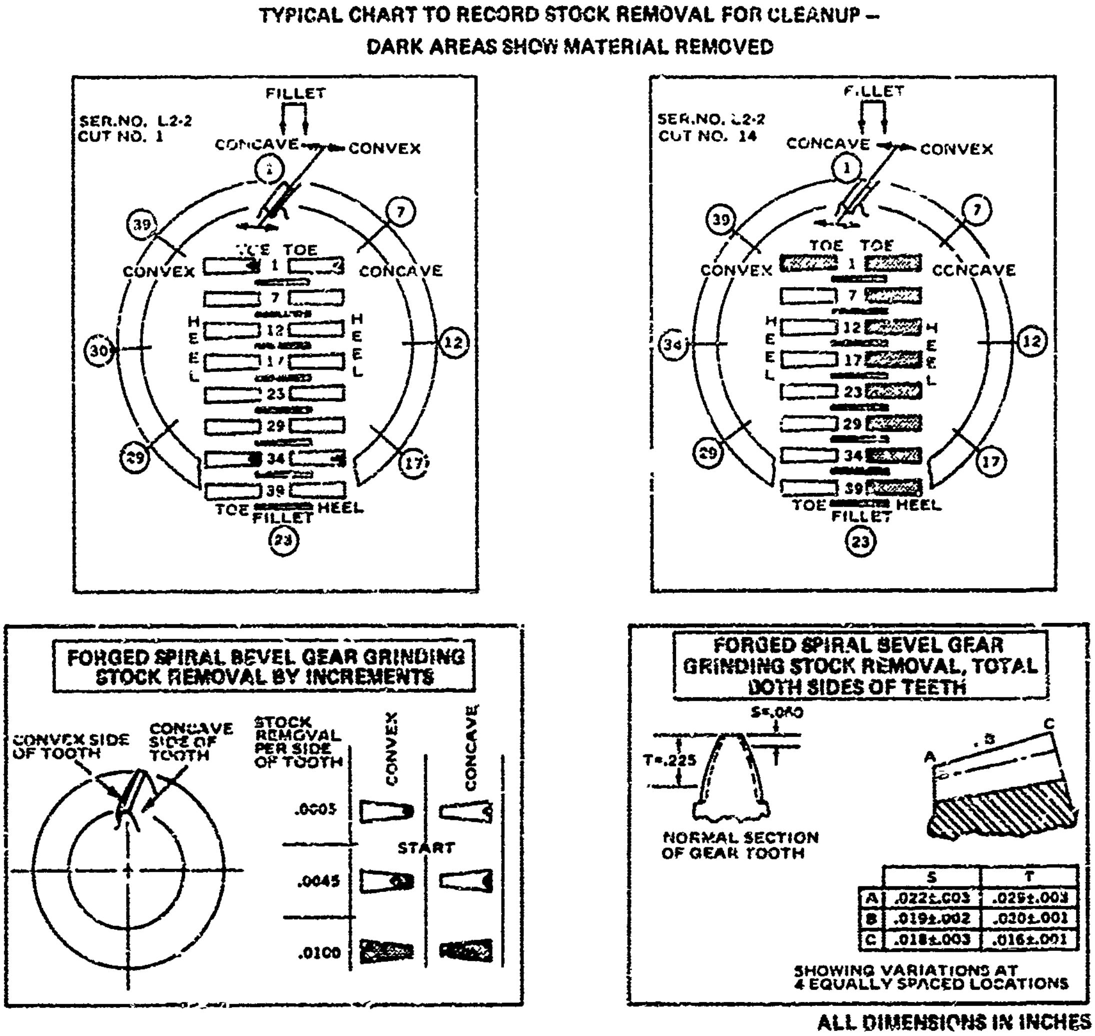


Figure 22. Grind Stock Removal Records

Table X
Grind Stock Removal Data

(44 Tooth Gear)

Identification	Toe (Inches) Add. .060	Toe (Inches) Add. .225	Center (Inches) Add. .060	Center (Inches) Add. .225	Heel (Inches) Add. .060	Heel (Inches) Add. .225
Frg. 2-2 (as-forged)	.019	.026	.016	.019	.015	.015
	.022	.029	.021	.020	.018	.016
	.026	.032	.021	.019	.021	.016
	.022	.029	.019	.021	.019	.018
Avg.	.022	.029	.019	.020	.018	.016
Variation	.007	.006	.005	.002	.006	.003
Frg. 2-6 (as-forged)	.021	.032	.023	.024	.021	.023
	.021	.032	.024	.029	.023	.021
	.025	.037	.028	.027	.024	.024
	.024	.033	.025	.027	.020	.025
Avg.	.023	.034	.025	.027	.022	.023
Variation	.004	.005	.005	.004	.003	.004
Frg. 204 (carburized & hardened)	.023	.024	.023	.022	.015	.018
	.025	.027	.018	.022	.014	.014
	.026	.027	.019	.025	.018	.020
	.027	.026	.024	.027	.016	.023
Avg.	.025	.026	.021	.024	.016	.020
Variation	.004	.003	.006	.005	.004	.009

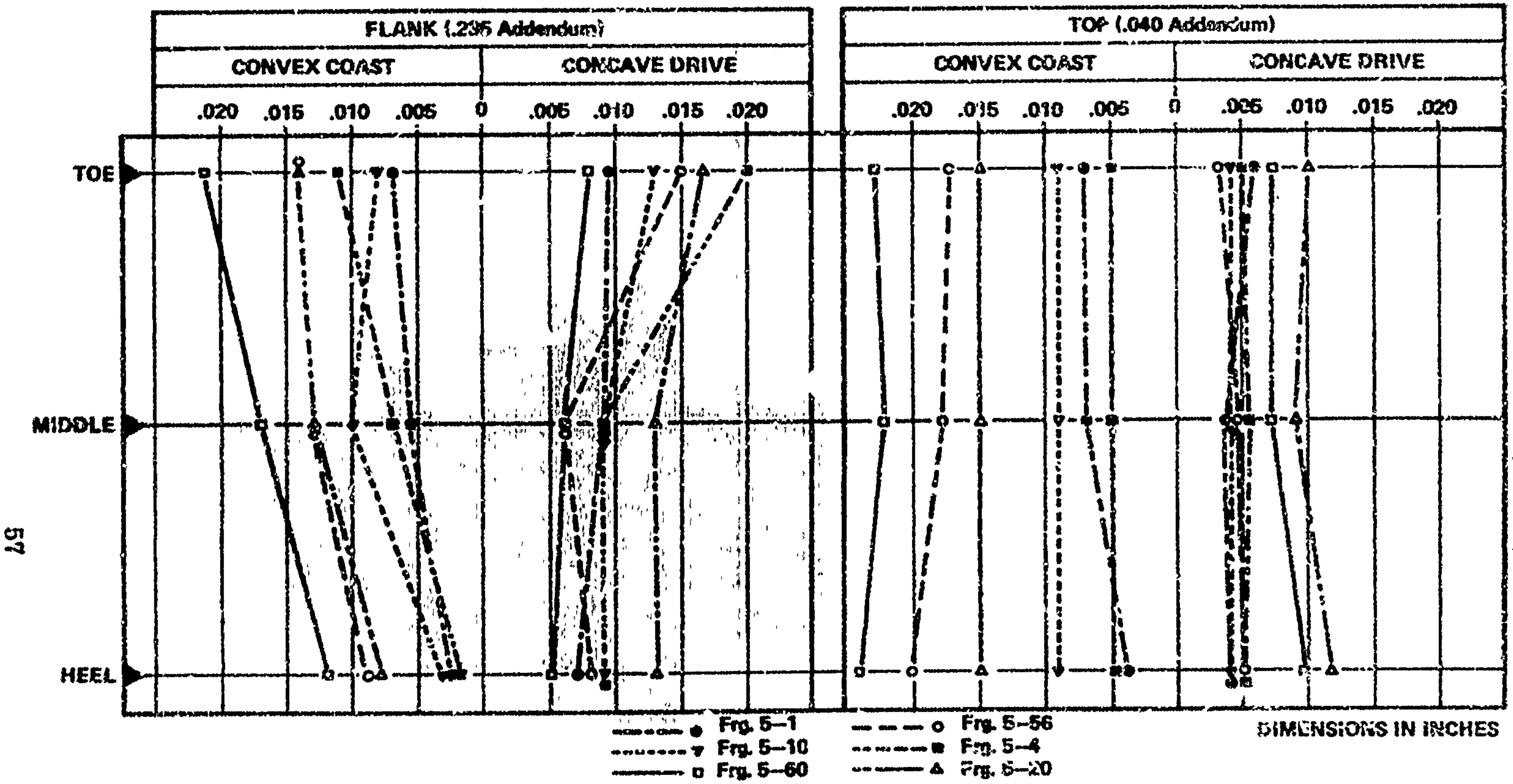


Figure 23. Amount and Distribution of Material Removed From Preproduction Forged Pinion Teeth by Clean-up Grind

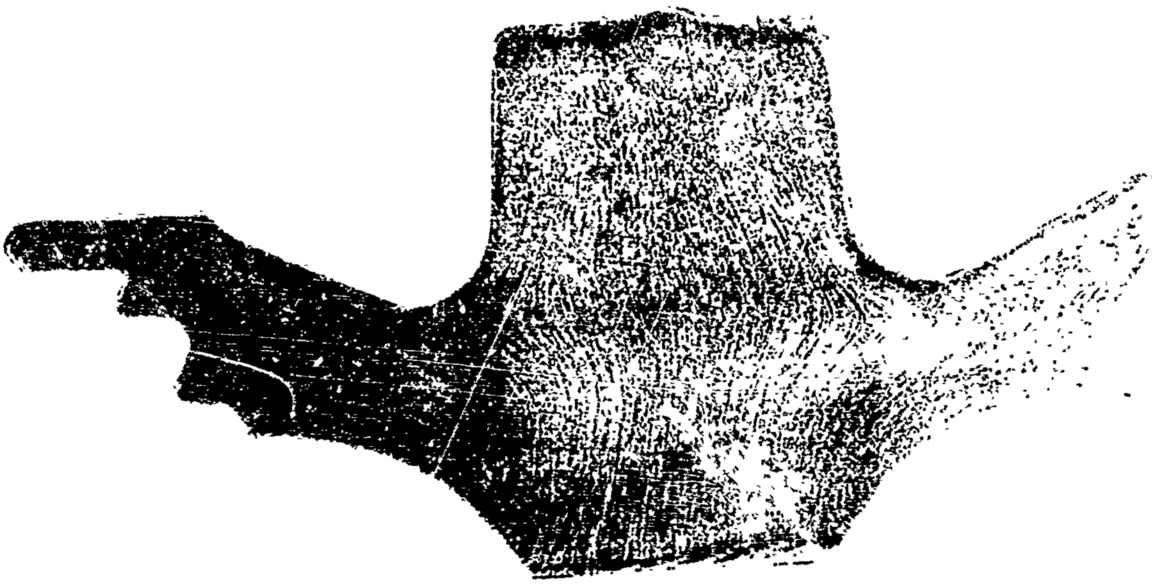


Figure 24. Forging Flow in the Spiral Bevel Gear

Figure 25. Forging Flow in the Spiral Bevel Pinion

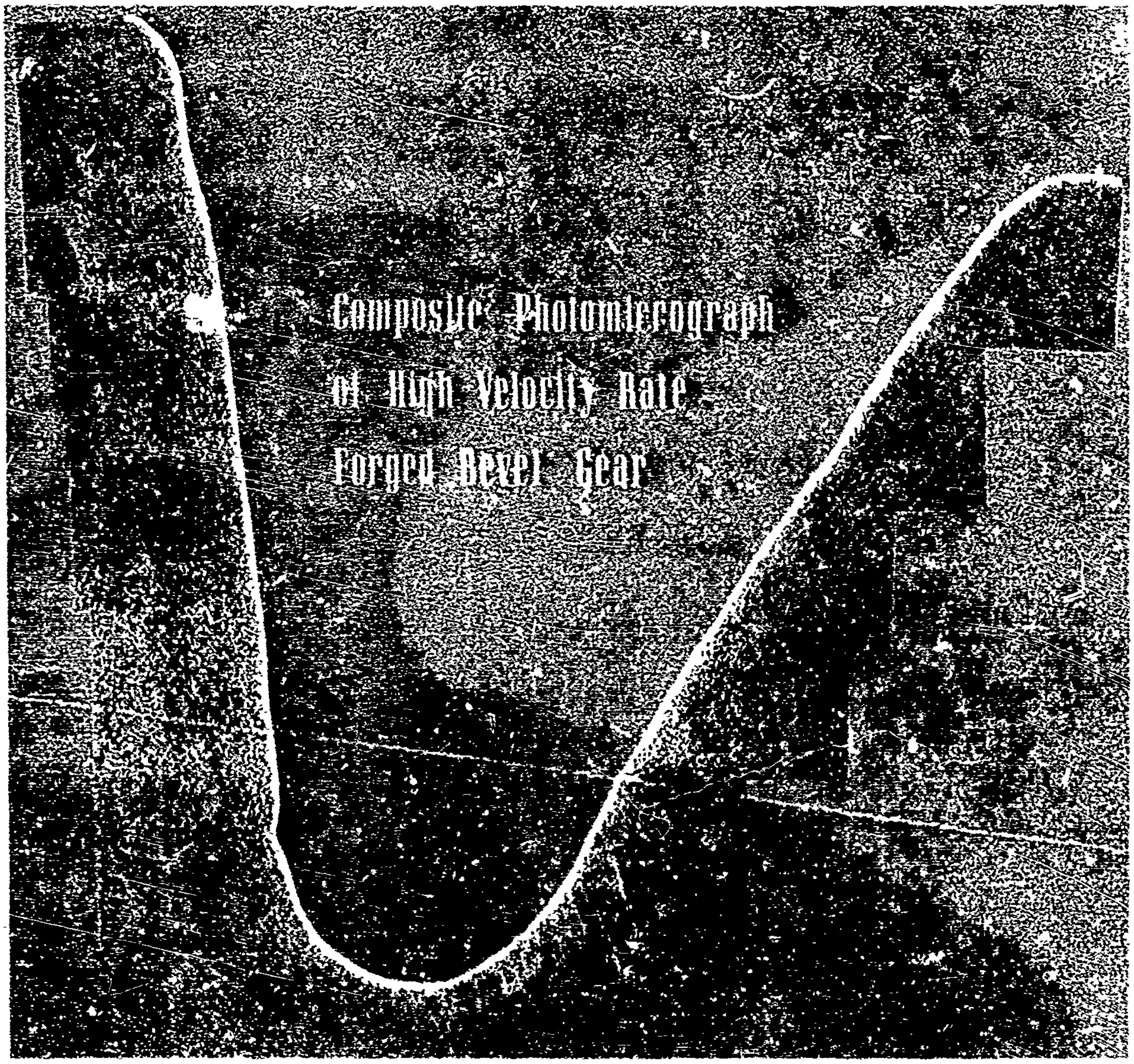


Figure 26. Flow Around the Tooth Root and Flank of the Spiral Bevel Gear Forging

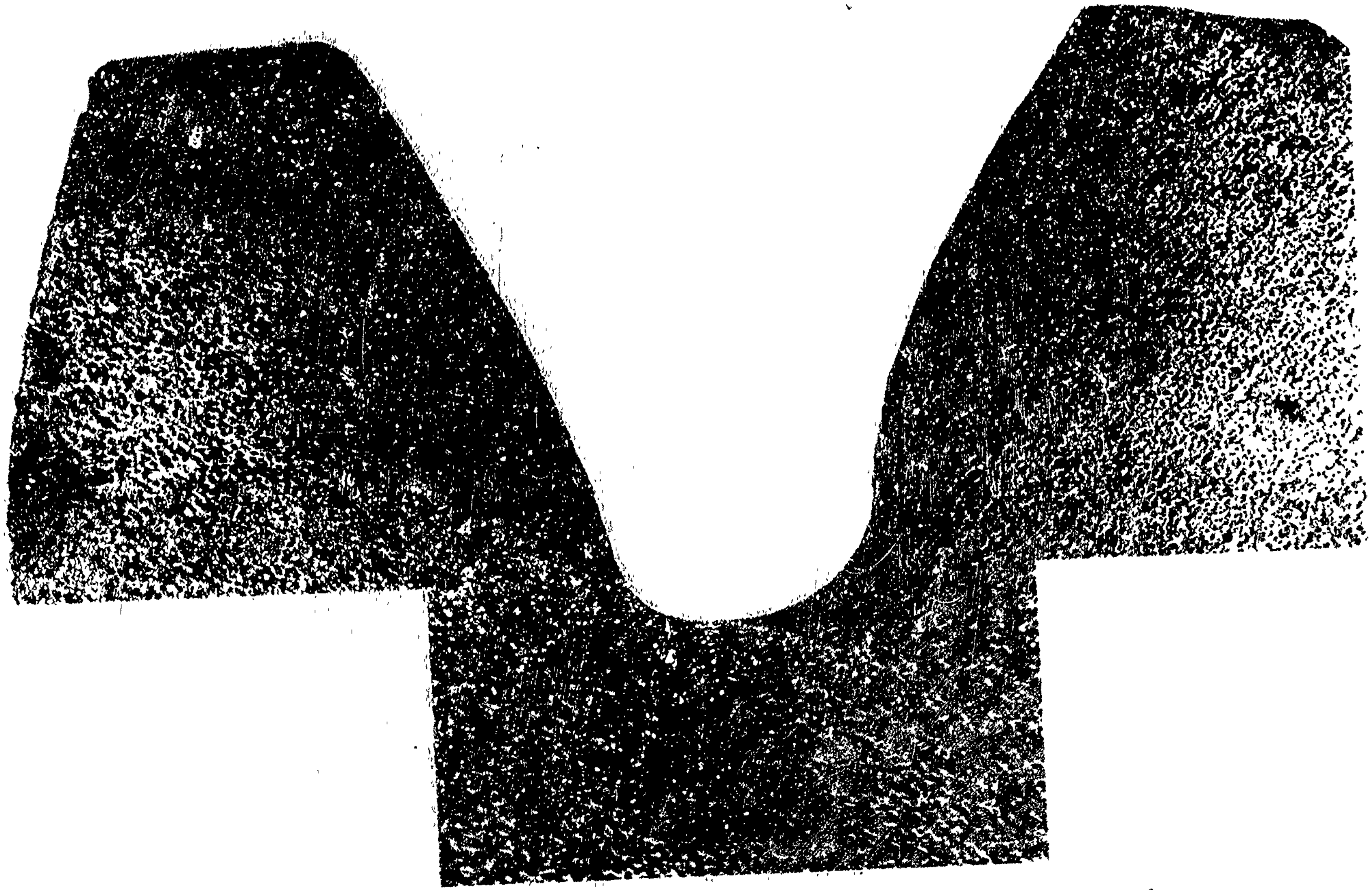


Figure 27. Flow Around the Tooth Root and Flank of the Spiral Bevel Pinion Forging

The results obtained indicate that a typical up-set type flow pattern is produced in the hub which extended radially into the tooth section with a restrictive densification effect being produced around the tooth root and flank as the metal flow filled the section and progressed longitudinally towards the flash area. The extremely fine flow pattern characteristics of the tooth section as compared to that of the adjoining hub section, indicates that a very high order of metal flow and reduction refinement is produced in the tooth elements in conjunction with the development of the preferential flow.

Decarburization and grain size tests of the billet, preform and finish forged material indicated that the forging conditions, heating and processing did not appreciably alter the surface carbon composition or grain size except for a slight increase in the tooth section, as evidenced by the following test results:

	Grain Size	Partial Decarb.
Billet (AMS 6265)		
Outside:	5-6 (Occasional 3)	0.006"
Center:	6-7	
Preform Forging (AMS 6265)		
Taper area	6 (Occasional 4)	0.004"
Finish Forging (AMS 6265)		
Tooth:	3-6	0.008"
Center:	6-7	

The grain size photomicrographs of the billet and finish forging are shown in Figure 58.

A summary of the program results shows that:

a. Die sets for forging the spiral bevel gear sets were designed, manufactured and redesigns incorporated as necessary.

b. Developmental forging procedures were established for the spiral bevel gear set and pinion preproduction.

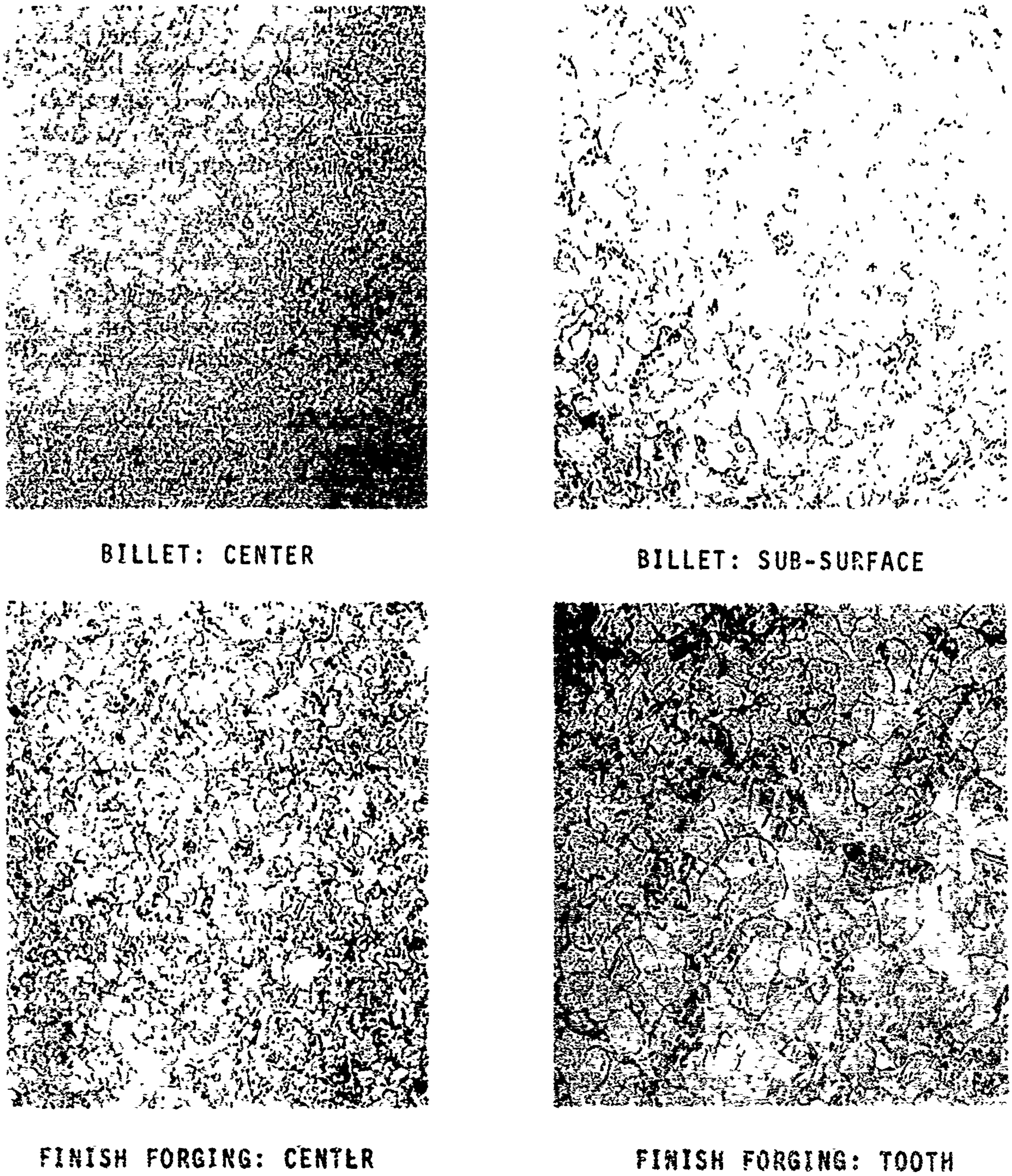


Figure 28. Grain Size Photomicrographs of the Billet and Finished Gear Forging 100x

c. Gross dimensional deformation of the block and finish die cavities and finish die cavities occurred throughout all phases of the development forging and the pinion preproduction forge run.

d. Dimensional and stock removal evaluations of the forgings indicated that:

   1. The 0.0125"/" shrink allowance factor was correct for high velocity forge die design usage.

   2. Maximum variation of tooth thickness of individual forgings ranged from 0.002" to 0.008".

   3. Variation of tooth thickness of a combined forge lot was 0.014" maximum.

   4. Forged tooth thickness was in excess of the pregrind thickness by 0.006" to 0.024".

The net effect of the forged tooth inspection results was that the finish die cavities would require rework to reduce the forged tooth thickness and provide a uniform distribution of the grind stock material. The required corrections to the die would normally be obtained by an appropriate adjustment to the electrode tooth geometry and the in-feed helix lead of the EDM guide fixture. However, in view of the demonstrated gross dimensional instability condition of the die cavities and the unknown quantitative effect it may have had on the tooth dimensional data, further rework of the dies to obtain a minor dimensional adjustment was considered inappropriate.

Die Deformation

The large amount of tooth deformation experienced in the forgings can be attributed to two causes:

a. The spiral tooth geometry, especially in conjunction with the small cone angle of the pinion causes intolerably large forces on the tooth part of the forging die.

b. The deleterious tempering effect caused by excessive dwell time of the hot forged part in the die cavity. In subsequent meetings with several forging experts, it was generally agreed that one second was the maximum time the forging could be in intimate contact with the die material without harmful effects.

CONCLUSIONS

1. Forged spiral bevel gears with integral teeth can be produced by the high velocity pneumatic-mechanical closed die forge method in limited quantities before excessive die deformation occurs, having the following characteristics:

    a. Development of preferential forging flow in the hub and tooth elements.

    b. Maximum tooth thickness variation of .008" for individual forgings and .014" for a forge lot.

2. The current "state-of-the-art" technology for high velocity forge die design and die material combinations is not adequate for production forging spiral bevel gears to pre-grind tooth thickness requirements. Program results indicate that further development of high velocity forge die design, material and hardness combinations are mandatory.

3. It is concluded that the methods, forge procedures and dies that were developed and utilized for the performance of this program are, in fact, adequate for producing spiral bevel gears, with integrally forged oversize teeth, for finish processing with a light profile development grind, heat treating and finish grinding to size.

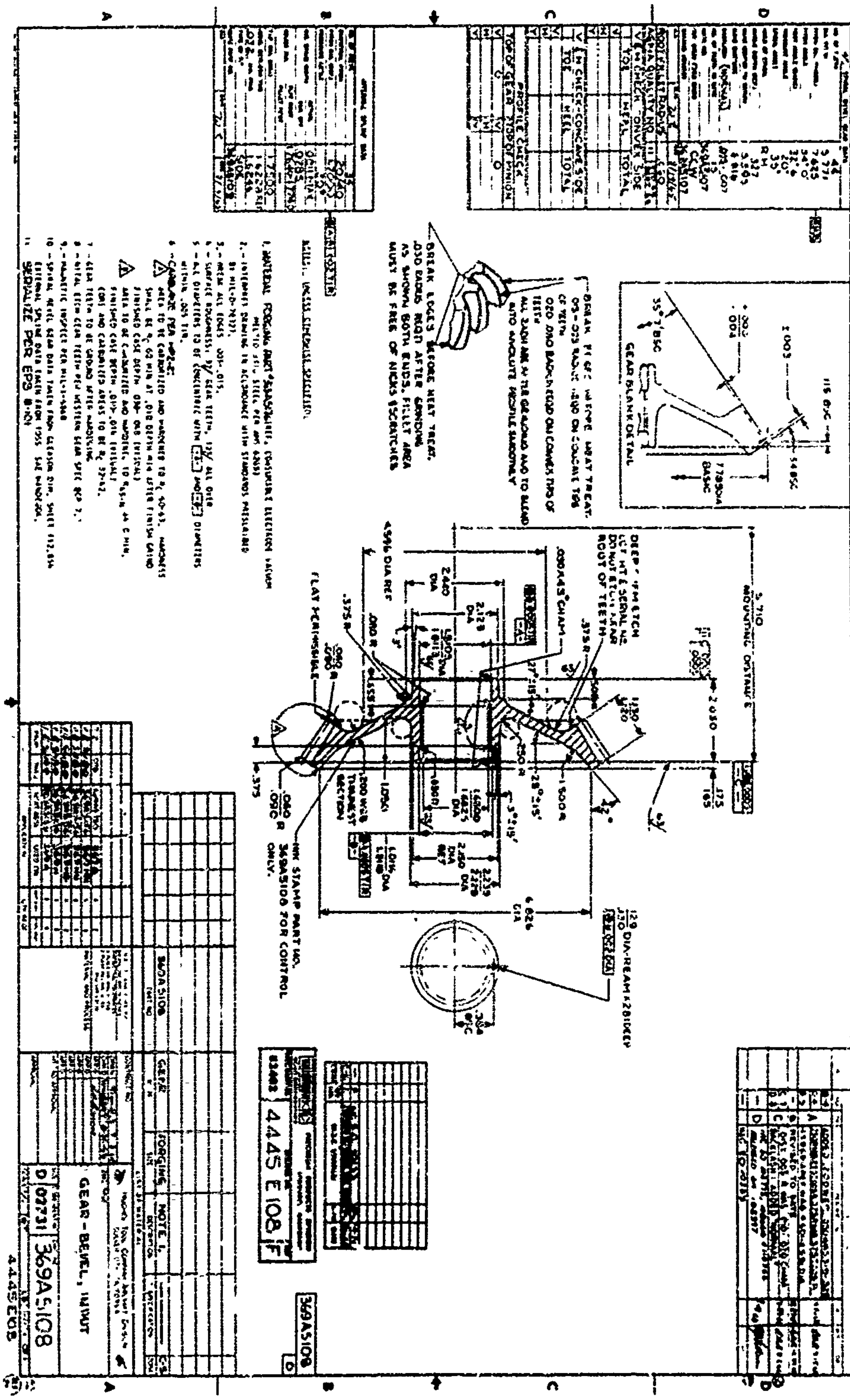
4. Excessive deformations of the dies occurred as the results of various conditions described in the body of the report. In addition to the development of die design to suit individual requirements, it is concluded that regardless of the basic design and the development of metallurgical properties of a high-velocity forging die-set, one additional requirement must be met. An ejection device must be part of the die-set. The finished forging and the die must not be allowed to remain in intimate contact (after the forging has been produced) for a period of time estimated to be in the region of one second in order to avoid deleterious softening of the die surfaces.

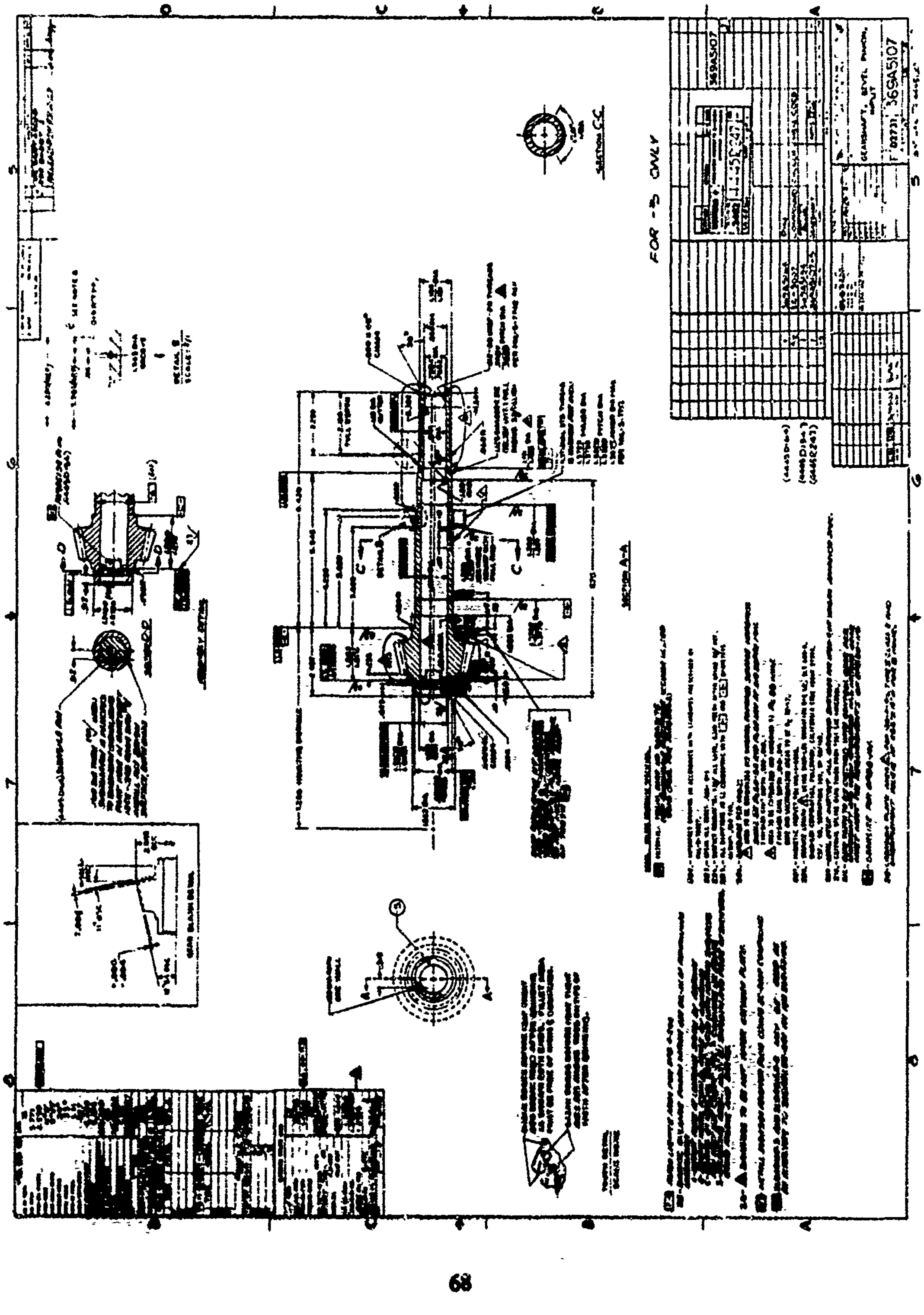
RECOMMENDATIONS

It is recommended that further development effort should be made regarding the design, material selection and heat treatment of the forging die sets. This should be done in order to achieve the required dimensional accuracy of spiral bevel gear forgings whose integrally forged teeth could be held to pre-grind tolerances.

APPENDIX I

ENGINEERING DRAWINGS FOR SPIRAL BEVEL GEAR SET USED FOR PROGRAM DEVELOPMENT


GEAR - BEVEL, INPUT
369A5108
4445 E 108



NOT REPRODUCIBLE

APPENDIX II

ANALYSIS OF THE SHRINKAGE CHARACTERISTICS OF FORGED SPIRAL BEVEL GEARS

Since homogeneous isotropic material is assumed, the shrinkage of gears from the as forged condition can be considered as a thermo-expansion problem. Consider a solid body subjected to a temperature change ΔT throughout. Imagine that this body is held to the same form and volume. Now a compressive stress of $\Delta T \alpha E/(1-2\upsilon)$[1] must be applied on the boundary of the body so the elastic strain would cancel the thermal strain. In the actual body, there is no such compressive stress applied on the boundary, so this stress must be relaxed by applying an equal and opposite stress on the boundary. This applied stress has the same effect as the identical body subjected to a negative hydrostatic pressure. This enables the calculation of strain distribution of a body with known temperature change throughout by calculating the strain distribution of an identical body with no temperature change but with the equivalent surface force (Ref. 1).

Investigating the shrinkage characteristics of the forged gears by this approach shows that shrinkage is uniform and predictable and that no distortion can be expected other than normal shrinkage due to thermal gradients. Hence the die geometry can be developed from the theoretical gear geometry by applying only the normal shrinkage values for the forging temperature to all dimensions.

1. Roark - Formulas for stress and strain, 3rd Edition P. 335 3.
"A solid body of any form is subjected to a temperature change ΔT throughout, while held to the same form and volume. The resulting stress is $\Delta T \alpha E/(1-2\upsilon)$ compression.

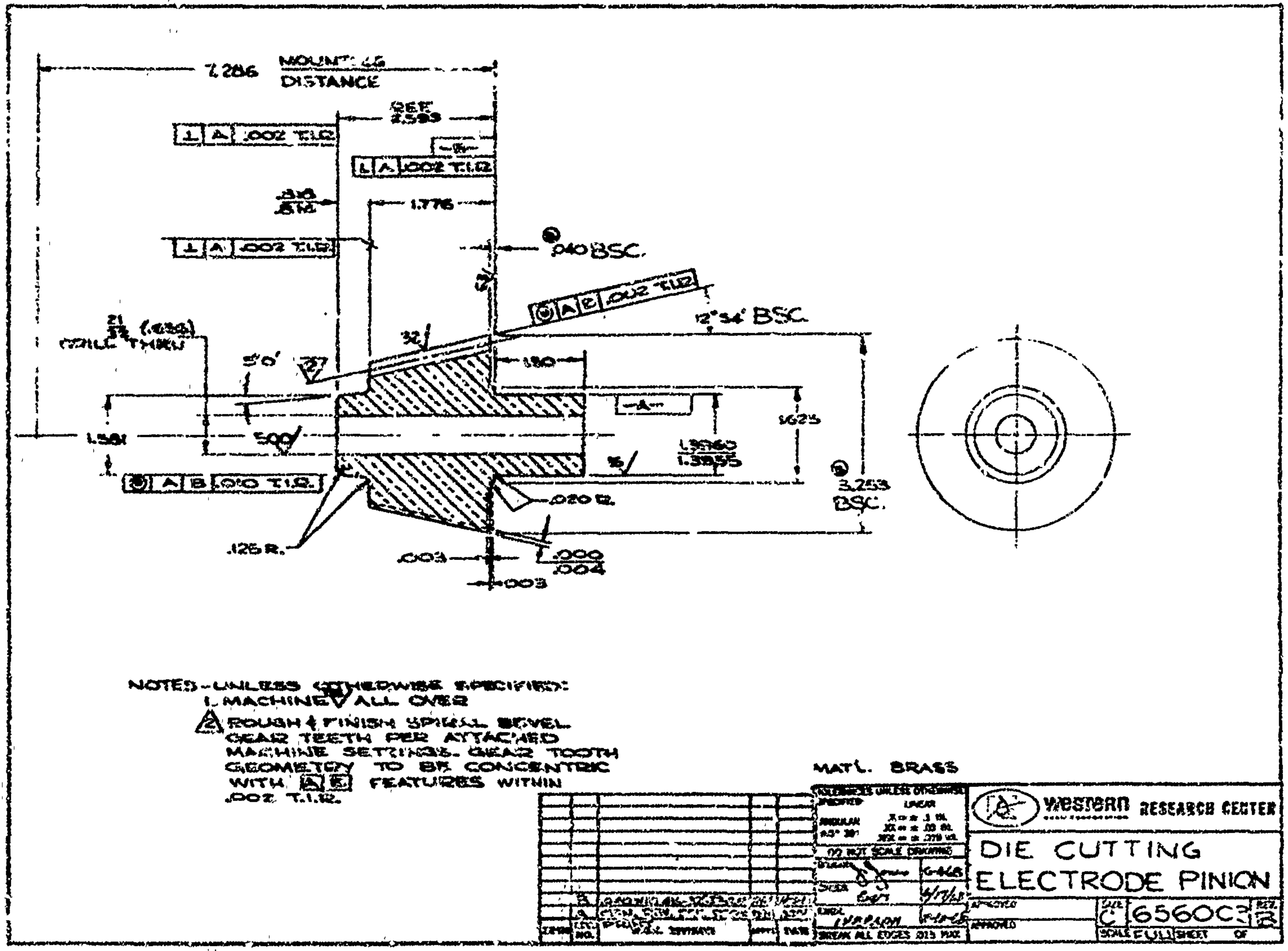
REFERENCES

1. Morgan, A. J. A., "A Proof of Duhamel's Analogy for Thermal Stresses." J. Aero/Space Sciences, Vol. 25, pp. 466-467, July, 1958.

2. Sokolnikoff, I. S., "Mathematical Theory of Elasticity". Chapter 3.

APPENDIX III

ENGINEERING DRAWINGS FOR EDM ELECTRODES


7.286 MOUNTING DISTANCE
REF. 2.593
.002 T.I.R.
1.776
.040 BSC.
12°34' BSC
.180
21/32 (.656) DRILL THRU
5°0'
32
1.581
.500
.010 T.I.R.
1.3960
1.3955
1.625
3.253 BSC.
.020 R.
.125 R.
.003
.000
.004
NOTES - UNLESS OTHERWISE SPECIFIED:
1. MACHINE ALL OVER
2. ROUGH & FINISH SPIRAL BEVEL GEAR TEETH PER ATTACHED MACHINE SETTINGS. GEAR TOOTH GEOMETRY TO BE CONCENTRIC WITH A B FEATURES WITHIN .002 T.I.R.
MAT'L. BRASS
DO NOT SCALE DRAWING
BREAK ALL EDGES .015 MAX
Western RESEARCH CENTER
DIE CUTTING
ELECTRODE PINION
C 6560C3 B
SCALE FULL

Unclassified

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DOCUMENT CONTROL DATA - R & D

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13. ABSTRACT

The objective of this project was to develop an alternate manufacturing method for spiral bevel gears used in Army helicopters. ~~(U)~~

This report covers the technical description of a program to develop high velocity forging techniques to produce spiral bevel gears to pre-grind tolerances. Initial objectives were to obtain as-forged gears with .005 inches excess material on the side of each tooth for finish grinding after heat treating. ~~(U)~~

The report includes a discussion of die design parameters, the manufacturing techniques for dies, forging parameters, dimensional checks of the forged gears, machining techniques for determining as-forged geometry and macroscopic and microscopic metallurgical data showing grain flow and micro-structure. ~~(U)~~

Also included is a discussion of difficulties experienced and recommendations for future investigations. ~~(U)~~

DD FORM 1473

Unclassified

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Security Classification

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
1. Alternate Manufacturing Method, Spiral Bevel Gears						
2. Dies, Forging						
3. Forging, Spiral Bevel Gears						
4. Helicopter Gears						
5. High Energy Rate Forging						
6. High Velocity Forging						
7. Spiral Bevel Gears						

Unclassified

Security Classification